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APPLICATION OF ABSORPTIVE TREATMENTS ON TRAFFIC NOISE BARRIERS IN FLORIDA

by

CHIN BOON CHUA
B.Eng. (Hons) University of Putra Malaysia, 2001

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Civil and Environmental Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

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2004

ABSTRACT

Traffic noise has been recognized as a nuisance in the United States and a problem affecting many Americans living close to highways during the past 3 decades. Barriers are frequently the only practical means of noise control when a highway passes through a densely populated area. However, reflections of noise path exist when single or parallel barriers are built to control noise. In the single barrier case, reflections may cause the noise levels to increase on the opposite side or the road and could exacerbate the problem and causes potential annoyance to nearby residents. In the parallel barriers case, the multiple sound reflections between barriers can cause reverberant build-up between them. Such reverberant build-up then constitutes a higher sound level, which can seriously degrade the acoustical performance or insertion loss expected from each wall.

In this thesis, the parallel barrier analysis feature in the Federal Highway Administration Traffic Noise Model (FHWA TNM), which is based on RAYVERB was used to explore the effects of multiple reflections due to single and parallel barriers and the use of absorptive treatment. Database was developed from the data collected from previous research efforts was used to generate a best fit equation model that can be used as a predetermining tool to determine the magnitude of parallel barrier insertion loss. The best fit equation model was then used to test against measured/model result and TNM prediction results for its validity. Absorptive materials

were also studied such that 3 top of them were selected and recommended for Florida highway barrier use.

It was found that the top three absorptive treatments for use on Florida highway barriers have been determined to be cementitous material, metal wool and glass fiber. These materials can be used to reduce the sound reflections for single and parallel barriers.

The developed best fit equation model from this research is $Deg = -2.17NRC - CW^{0.42} + 1.97\times\ln(BH) + RH^{0.29} + DBB^{0.27}$; the prediction results give moderately high R^2 value of 0.55 if compared to the results from database. Prediction results from best fit equation model was also found to be consistent with the results from the measure/modeled results, providing further proof of the validity of the model. However, if compared results from equation model, TNM and measured/model (measured and model compared results using ANSI method), TNM was shown to provide higher insertion loss degradation.

It was found that the most effective placement of absorptive material was the pattern which covers the barrier from the bottom up; it was also found that only about 60% from the bottom of the barrier area requires covering with high NRC absorptive treatment ($NRC \geq 0.8$) without sacrificing insertion loss. Also, if the barrier area near the top includes an easily obtainable NRC value of 0.4, only 40% to 50% of the bottom barrier needs absorptive treatment with a higher, more expensive NRC rating. These findings can substantially reduce the cost of conventional absorptive barrier which have full coverage of high NRC absorptive treatment.

This research has begun important improvements in noise barrier design, additional work can be continued to further verify all the findings in this thesis such that easier and better equation model can be developed to calculate insertion loss degradation and cheaper absorptive barrier with less absorptive material usage can be built.

This thesis is dedicated in loving memory of my mother, Yeow Sew Eng, who nurtured my body, tempered my spirit, and encouraged a thirst for education.

ACKNOWLEDGMENTS

This thesis could not have been completed without the help, support, and guidance of many people around me. I would like to take this opportunity to thank them and tell them that I appreciate their kindness and that I will always remember their willingness to contribute with profound gratitude.

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I heartily extend very sincere gratitude to my sponsor, Paul Langley, for his generosity, guidance, support, and patience which was freely given for the past three years since I first began preparations to go to America from my native Malaysia to pursue my education at the University of Central Florida, and to fulfill my dreams. He introduced me to America and taught me about her culture and ideals. I would not have had this opportunity or reached the next phase in my life without him.

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CHAPTER ONE: INTRODUCTION

Noise has been defined as unwanted or undesired sound. Noise is not only a nuisance but can also cause physiological and psychological damage to the human body. This can result from anything from hearing impairments to stress related illness. More typically, transportation noise interferes with communication, concentration, relaxation, and sleep; and results in annoyance.

Traffic noise has been recognized as a nuisance in the United States and a problem affecting many Americans living close to highways during the past 3 decades. Federal legislation addressing the issue of highway noise culminated in the U.S. Code of Federal Regulations Part 772 (23 CFR 772), “Procedures for Abatement of Highway Traffic Noise and Construction Noise.” This regulation and subsequent federal policies give guidance but allows the states latitude in determining the need for and type of highway noise abatement [Morgan, 2001].

Barriers are frequently the only practical means of noise control when a highway passes through a densely populated area. Data from 2001 show that more than 2,947 km (1,831 miles) of noise barriers have been built in the United States since the early 1970s at a total estimated cost of more than $ 2.5 billion (2001 dollars) [FHWA, 2003].

In the single barrier case, reflections may cause the noise levels to increase on the opposite side or the road and could exacerbate the problem and causes potential annoyance to nearby residents. If there are residential areas on both sides of a highway, two barriers or parallel barriers may be necessary. The problem with parallel barriers is that the multiple sound reflections between barriers can cause reverberant build-up between them. Such reverberant build-up then constitutes a higher sound level, which can seriously degrade the acoustical performance or insertion loss expected from each wall.

Special computer models have been developed for use in highway noise prediction and are capable of accounting for the degrading effects of multiple reflections between parallel barriers have been used in the past. Examples of those computer models are BARRIER and BARRIER-X [Fleming, 1990], IMAGE-3 [Bowlby, 1986] and RAYVERB [Menge, 1991]. In this thesis, the parallel barrier analysis feature in the Federal Highway Administration Traffic Noise Model (FHWA TNM), which is based on RAYVERB was used. This model was selected because it is the regulatory model required by the FHWA. The effects of multiple reflections due to single and parallel barriers and the use of absorptive treatment were explored in this work. The FHWA TNM is a new state-of-the-art computerized model used for predicting noise impacts in the vicinity of highways. It uses recent advances in acoustics and computer technology to improve the accuracy and ease of modeling highway traffic noise, including the design of efficient, cost-effective highway noise barriers [Lee, 2003].

Absorptive treatment is an effective way to prevent the degradation of acoustic performance of parallel barrier and to reduce impact due to reflective noises. If the barriers are made absorptive, most of the incident sound energy on a barrier is absorbed; the reflective path annoyance to the nearby residents will be significantly reduced. Also the reflections from the far wall will not compromise the performance of the near wall and so the effectiveness of the parallel barriers system will not be compromised.

The primary purpose of this research has been to better understand the multiple reflections and the application of absorptive treatment for use on noise barriers in Florida. There are 5 major objectives that were accomplished through this research:

1. The study of various absorptive treatments for highway noise barriers and selection of the most applicable in the Florida.
2. The study of the degradation of insertion loss of reflective parallel barriers for typical Florida cross-sections.
3. The examination of the impact of parallel barriers for wide Florida right-of-ways.
4. The placement and area of absorptive treatment on a noise barrier that is needed for typical Florida configurations.
5. Recommendations for the use of absorptive barriers in Florida.

CHAPTER TWO: LITERATURE REVIEW

The most common method of reducing highway noise impact on a community is the construction of traffic noise barriers [Fleming, 1992]. Since the early 1970s, more than 2,947 km (1,831 miles) of noise barriers have been built in the United States and by far, concrete has been used for noise barriers more than any other single material. Concrete traffic noise barriers account for 44.5 % of all barriers; followed by block and wood, with 25.7 % and 9.8 %, respectively. Metal, berm, and brick together account for approximately 6 % of the total. 12.3% of all barriers have been constructed with a combination of an earth berm and a wall on top. Of the remaining barriers, 0.9 % have been constructed with other materials such as recycled products, plastics, composite, polymers, etc. Of the barriers, only 1.4 % have been constructed with absorptive treatment (Figure 2) [FHWA, 2000]. The barriers constructed include 94 % between 2 m to 6.9 m tall (Figure 1), 2 % are less than 2 m and 4 % of them are more than 6.9 m tall [FHWA, 2000].

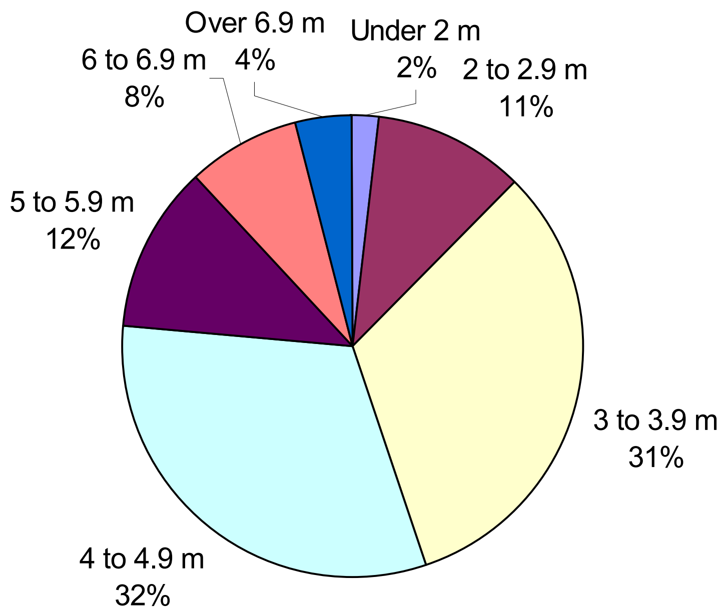


Figure 1: Percent of Total Noise Barrier Height by the Linear Length (km) [FHWA, 2000]

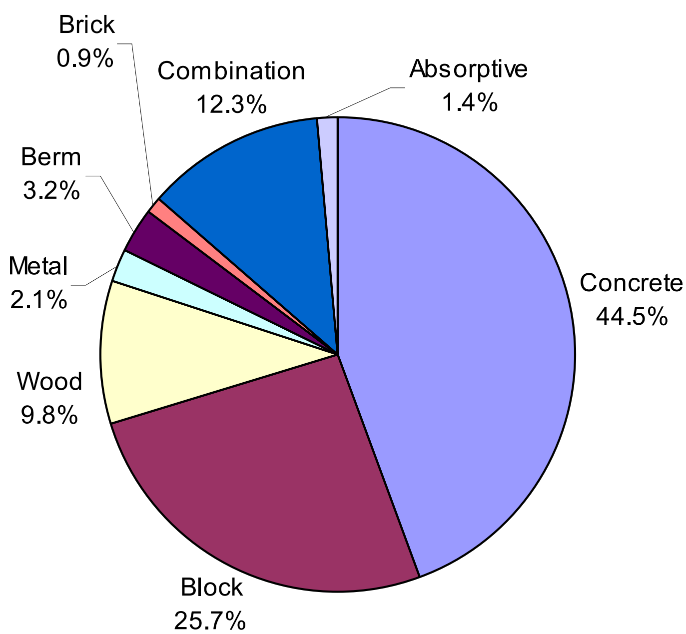


Figure 2: Percent of Noise Barrier Construction Nationally by Material Type [FHWA, 2000]

Consequences of putting up noise barriers to mitigate traffic noise are the possibility of reflecting noise from single barriers to the opposite site of the highway and multiple reflections between parallel barriers that could result in a degradation of acoustical performance. The amount of the reflected noise depends on the surface of the barrier. A hard, smooth surface such as a concrete, block, metal, wood and metal barriers will reflect most of the noise that strikes it and unfortunately vast majority of the barriers in the United States are constructed by these reflective materials as shown in Figure 2.

Single barrier reflections can cause the increase in noise level in the opposite site of the roadway; usually the increase in noise level is not perceptible by human ears. However, in some cases, overall increase in noise level can be perceived by residents due to the reflected noise path and will be discussed in detail later.

If residential areas exist on the both sides of the highways, parallel barriers may be necessary to protect residents from traffic noise pollution. However, the sound abatement capability from the barriers may be compromised due to the multiple reflections that occur in the canyon between the barriers. The degradation of performance of the parallel reflective noise barriers from traffic noise has been investigated extensively since the early 1970s. Although most experts believe the multiple reflections are the reason for the acoustic degrading performance, there are conflicting opinions on the magnitude of the problem.

Studies show that two effective ways to prevent the degradation of the barrier performance is to either tilt the barriers or make the barriers sound absorbing. If the barriers are made sound absorbing, the multiple reflections that cause the reverberant build-up to compromise the performance of the barriers will be greatly reduced in intensity.

Basic Sound Wave Interaction with Partition

When a sound wave is incident on a barrier that has a large flat surface compared to the wavelength, the sound wave will reflect back with the equal angle of the incidence wave. The intensity of the sound wave can be predicted as if there was an image source behind the barrier some distance away. This type of reflection is also known as a "specular" reflection. However, if the barrier has irregularities in it, the sound wave will reflect back with different directions and this is called diffusion. The intensity of the specular reflection is actually reduced by the intensity of the surface diffusing the sound wave. Figure 3 illustrates the interaction of sound waves generated from a source and the interaction with a sound barrier. The source, S, propagates sound in all directions and some passes through the barrier, some is reflected, and some travels over or around (diffracted) by a partition to a receiver, R.

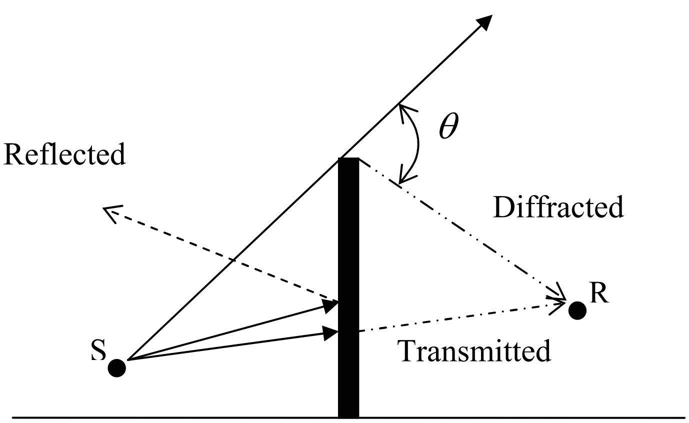


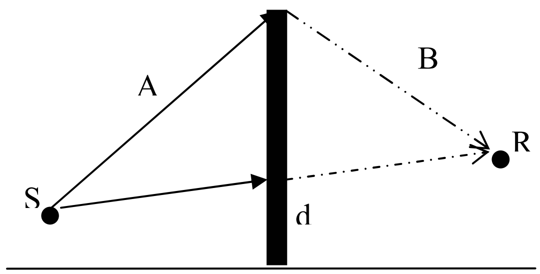
Figure 3: Interaction of Sound Waves with a Partition

Transmitted sound depends on the barrier's solidity and weight per unit area. The sound energy that passes near the edges of the barrier will "bend" over the top edge or around the corner, but in reduced intensity to the other side by the phenomenon called "diffraction". This diffracted energy is a function of the diffracted angle θ; as θ increases the attenuation of the diffracted energy also increases. Diffracted sound depends on the height and length of the barrier in relation to the source and receiver. An important aspect of the diffraction is the path length difference (δ) between the diffracted paths from source to receiver as if the barrier were not present. This path length difference is used to compute the Fresnel number N, which is a dimensionless value used in predicting the attenuation provided by a noise barrier positioned between a source and a receiver [Fleming, 2000]. The Fresnel number N is computed as follows:

$$N = 2 \cdot \frac{\delta}{\lambda} \tag{1}$$

where N = Fresnel number
δ = Path difference determine along the path
λ = Wavelength of the sound radiated by the source

Figure 4 illustrates the path length difference while Figure 5 can be used in order to determine the attenuation provided by a noise barrier combining the Fresnel number calculated from the Equation 1 and Figure 5.



Path Length Difference δ = A+B-d

Figure 4. Illustration of Path Length Difference

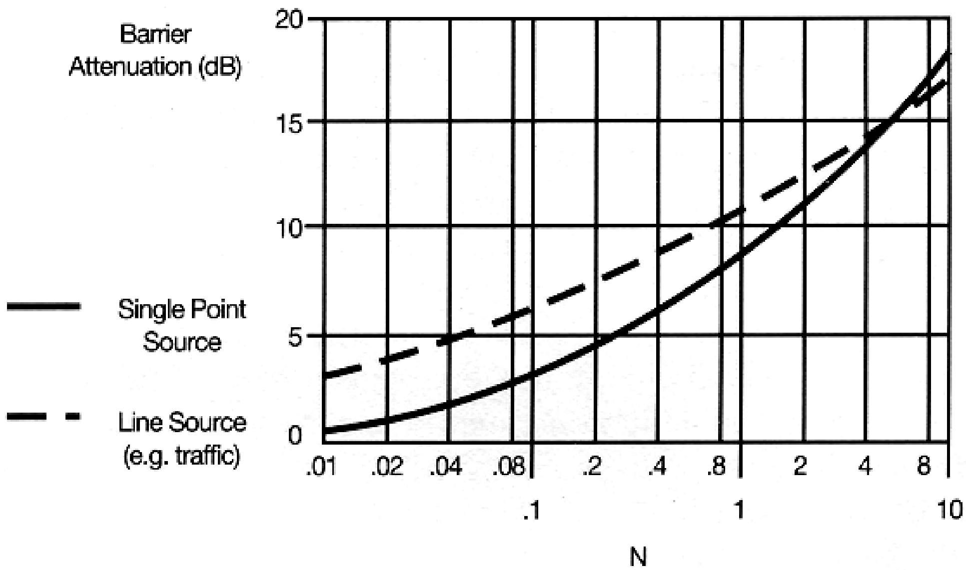


Figure 5. Partial barrier noise attenuation analysis [Cowan, 1994]

Reflected sound depends on the surface size and texture as previously stated. If the texture is changed in various ways, the phenomenon of sound absorption on a surface can be used to reduce the reflected sound energy.

The difference between the sound levels at the receiver before and after the wall is built is called insertion loss, and is the true measure of effectiveness. Insertion loss depends on all of the phenomenon previously listed as well as ground effects, shielding from other objects, and local topography.

The difference between the insertion loss when only near wall is built and the insertion loss when both near and far wall (parallel barrier) are built is defined as the barrier insertion loss degradation, Δ_{IL}. Mathematically, it can be described as:

$$\Delta_{IL} = IL_1 - IL_2 \qquad \text{(dB)} \tag{2}$$

where IL_1 = insertion loss due to single barrier
IL_2 = insertion loss when parallel barrier exits

A-weighted Sound Pressure and Equivalent Sound Pressure Level

The normal hearing response of a healthy human ear ranges from 20 to 20,000 Hertz (Hz). However, human ears do not sense all the different frequencies in the same manner but tend to attenuate sound from low frequencies and very high frequencies as well as amplify sound slightly from 2 kHz to 4 kHz range. This phenomenon can be explained from Figure 6 of the equal loudness contours. The equal loudness contours rise at both low and high frequencies and this means that at the same phon, human ears attenuate lower and higher frequencies such that a higher sound pressure is needed to produce the same loudness. This would appear reasonable to build into the sound level meter the same characteristic and consequently, A-weighted scale was developed. A-weighted scale has been developed as a set of filters in sound level meters to simulate the frequency sensitivity of the human hearing mechanisms. The reported A-weighted sound pressure levels are in the unit of dB(A). Table 1 specifies the weighting for each octave band used to produce an A-weighted sound pressure level.

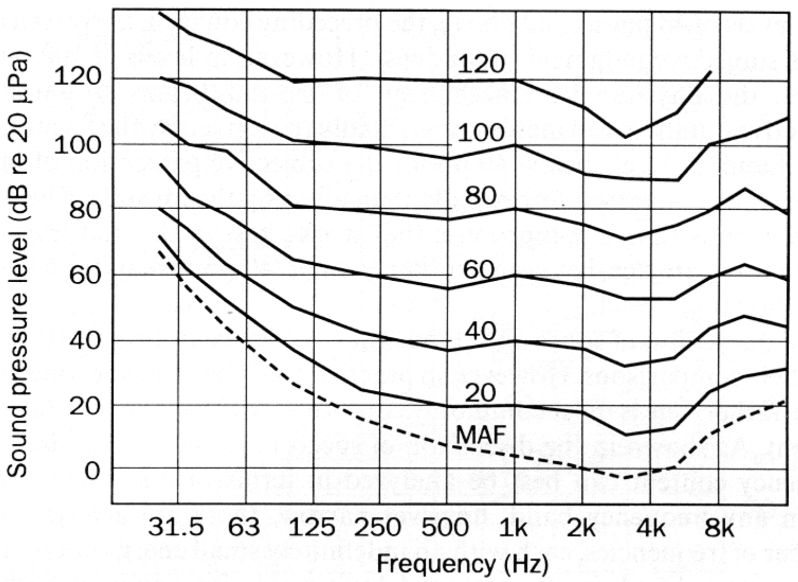


Figure 6: Contours of Equal Loudness, in phons. [Bies, 1996]

Determined relatives to the reference level at 1000 Hz
MAF – minimum audible field

Table 1: A-weighting of Octave Band Levels

Center Frequency (Hz	A-weighting adjustment
31.5	-39
63	-26
125	-16
250	-9
500	-3
1000	0
2000	1
4000	1
8000	-1
16000	-7

Table 2 shows the subjectively judged loudness by typical individuals. It is shown that in order for human ears to perceive the changes of the loudness, the change in sound level has to be at least 3 dB. It is also shown that a group of noise sources all producing the same amount of noise would have to be reduced by 10 dB to achieve a reduction in apparent loudness of one-half.

Table 2: Subjective Effect of Changes in Sound Pressure Level [Bies, 1996]

Change in Sound Level (dB)	Change in Power		Change in Apparent Loudness
	Decrease	Increase	
3	1/2	2	Just perceptible
5	1/3	3	Cleary noticeable
10	1/10	10	Half or twice as loud
20	1/100	100	Much quieter or louder

Traffic noise levels vary with time, depending on parameters such as traffic volume and composition, speed, and distance from the road [Bowlby, 1984]. These variations lead to various descriptors being used for traffic noise analysis. In the United States, the most common descriptor is an acoustic averaging function called the equivalent sound level, or L_{eq}. The L_{eq} is defined as single value descriptions of average sound exposure over various periods of time period from t_1 to t_2 and the equation for L_{eq} is shown below.

$$L_{eq} = 10\log\frac{\sum 10^{dBA/10}}{(t_2 - t_1)} \tag{3}$$

Units can be A-weighted resulting in L_{Aeq}. The FHWA uses $L_{Aeq(1hr)}$ for the worst hour of the day to determine if impacts occur along the highway facility.

Sound Reflections

Single Barrier Reflections

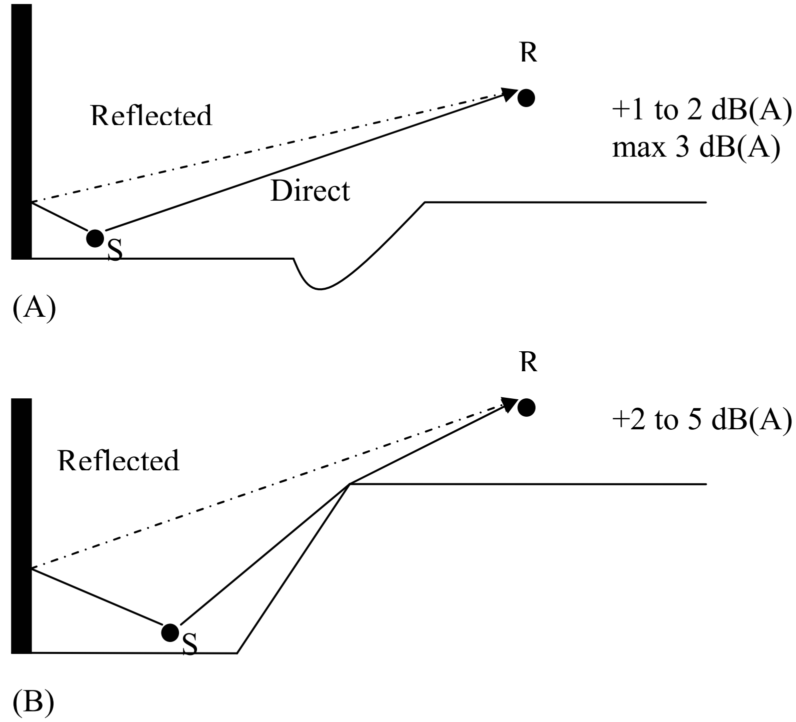


Figure 7: Single Barrier Reflections for Unprotected Receiver with (A) Unshielded Cut and (B) Shielded Cut [Caltrans, 2002]

As noted from Figure 7, for case (A), the receiver is exposed to the direct noise from the roadway before the barrier has been built. After the barrier is built, the receiver does not only receive the direct noise from the traffic but also the noise from the reflective path striking back from the barrier. Theoretically, for a cross-section analysis, this would add 3 dB(A) to the noise level at the receiver when 100% of the sound energy is reflected. However, in reality, the barrier is not a perfect reflector and due to the blockage of noise path from traffic stream, the increase in noise level is unnoticeable and cannot be perceived by human ears with only 1 to 2 dB(A)

[Caltrans, 2002]. For case (B), the receiver is shielded by the top of the cut and only exposed partially to the direct noise from diffraction. However, after the barrier is built, the receiver loses the benefit part of the shielding from the barrier due to reflective paths being at a higher elevation than the source and receives more acoustic energy. This situation can create a problem because the noise level can increase by 2 to 5 dB(A) [Caltrans, 2002] which is noticeable and can be perceived by a health human ear.

Parallel Barrier Multiple Reflections

When a highway passes through a densely populated area with residential areas on the both sides, two barriers may be necessary for the noise control and they are normally parallel to each other. In such instances, the emitted sound from the traffic may be reflected back and forth within the barriers and compromised the noise reducing capabilities of each barrier. The reason for this compromise is illustrated in Figure 8.

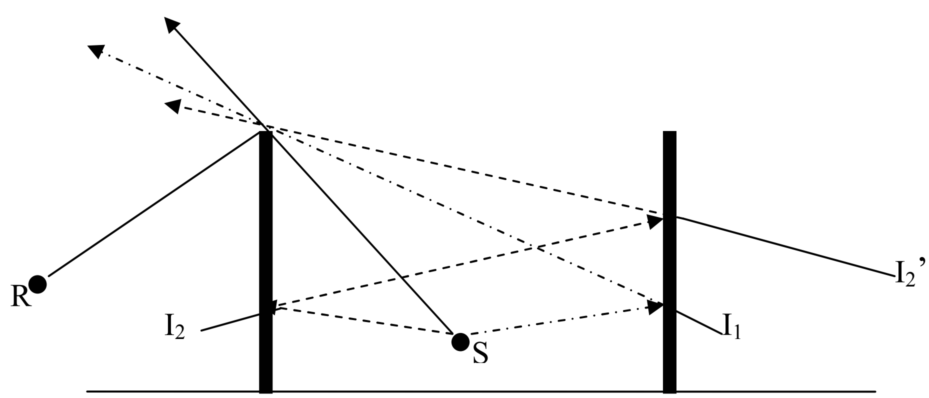


Figure 8: Multiple Sound Reflections for Parallel Barrier showing First Image (I_1, I_2) and Second Image (I_2') Sources.

As noted above from the figure, the sound energy from source S reaches the receiver R by diffraction over the top of the barrier. In addition to this acoustical energy, sound waves also reflect back and forth from the parallel barrier and diffract over the top of the near wall to the receiver R as illustrated in Figure 8. This sound energy from the reflections within parallel barrier can be conceived of as coming from an image source such as I_1, located behind the right barrier. Similarly, there is another image source I_2' that is caused by two reflections before the sound passes over the near barrier to the receiver. Note that the first reflection actually occurs on the near barrier at I_2. Energy from these image sources then contribute to the total energy reaching the receiver.

The actual number of images that theoretically occur, and their acoustic intensity will depend on, among other parameters, source position, wall heights, and canyon width. Each time the sound of a subsequent image diffracts over the top, the total sound energy at the receiver is increased.

Sound Absorption

In general, an effective way to prevent sound reflection problem is to apply sound absorptive treatment. The sound absorptive treatment will absorb sound energy before the sound wave is reflected from a noise barrier. As such, a greatly reduced amount of the energy from the image sources is added to the total energy and reduced amounts of sound energy will be reflected from a highway noise barriers reducing annoyance for the nearby residents.

The effectiveness of sound absorbing is rated by absorption coefficient, α.. The frequency dependent absorption coefficient is defined as the fraction of sound energy absorbed as compared to the energy striking the surface. The coefficient α is extremely frequency dependent and theoretically ranges from 0 to 1. If $\alpha = 0$, the material absorbs no sound and reflects the entire sound energy incident to it. If $\alpha = 1$, the material absorbs all sound energy incidents on it and reflects none. Mathematically,

$$\alpha = \frac{sound\ energy\ absorbed}{incident\ sound\ energy} \tag{4}$$

Absorption coefficients are sometimes reported as being greater than 1.00. These high values maybe seem to contradict with the definition of the absorption coefficient. However, diffraction effects at the edge of the test sample can explain sound absorption coefficients greater than one. One should assume no material has an absorption coefficient greater than one when selecting the absorptive materials. According to the definition of the sound absorption coefficient by Florida Department of Transportation (FDOT) in the recent Sound Barrier Acceptance Criteria, the sound coefficients shall be normalized so the highest value is no greater than 1.00 [FDOT, 2003].

A single number rating system for absorption coefficients over the human speech frequency range is known as the noise reduction coefficient (NRC). The NRC is defined in American Society for Testing and Materials (ASTM) Standard C423-02a, *Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method*, as the average of absorption coefficients for the octave band frequencies of 250, 500, 1000, and 2000 Hz, rounded to the nearest 0.05 dB [ASTM, 2003]. Equation 5 shows the mathematical form of NRC and Table 3 shows common materials with their associated NRC values.

$$NRC = \frac{\alpha_{250\,HZ} + \alpha_{500\,HZ} + \alpha_{1000\,HZ} + \alpha_{2000\,HZ}}{4} \tag{5}$$

Table 3: General NRC Characteristics for Common Materials [Cowan, 1994]

Absorption Characteristics	NRC	Materials
Highly Absorptive	1.0	• Materials designed specifically for high acoustical absorption
	0.9	
	0.8	
	0.7	
	0.6	• Typical suspended porous ceiling title • Typical audience in upholstered seats
	0.5	• Heavy Curtain • Grass • Upholstered seats
Moderately Absorptive	0.4	• Rough soil • Typical audience in wooden or metal seats
	0.3	• Heavy carpet on concrete
Reflective	0.2	• Unoccupied wooden or metal seats • Light multipurpose carpet • Trees
	0.1	• Light Curtain • Glass window, wood paneling • Plaster, gypsum board
	0	• Smooth concrete, painted brick, marble, glazed title, water surface

Sound Absorptive Treatment

Absorptive Systems for Highway Noise Barriers

The mechanism of sound absorption is that the acoustic energy of the sound is converted to some other form of energy – usually heat. There are several types of systems that are used for sound absorbing barriers [Watts, 1995].

1. **Hollow box systems with perforated panels containing fibrous material.** For this system the barrier panels are designed so that the side facing the traffic is perforated in order to allow the transfer of acoustic energy into the fibrous material contained within the box. The opposite side of the barrier is not perforated so that sound cannot readily be transmitted through the panel and a high transmission loss is maintained. The fibrous material usually consists of glass fiber or mineral wool, and is often protected by a thin layer of woven glass fiber to maintain dimensional stability.
2. **Systems that use panels constructed with open-textured porous materials.** For these materials, absorption is achieved by frictional losses in the connected voids of the permeable layer. Examples include:
    a. Panels constructed from specially fabricated concrete which results in a relatively light open porous structure to the facing.
    b. Panels made from treated and compacted wood shavings bonded with cement as a back panel to prevent transmission through the barrier.
    c. Panels constructed from compressed coated flint particles.

    A solid impermeable backing is usually required with these systems to prevent sound being transmitted through the panel, unless the panel is thick enough without this.

3. **Systems containing resonant cavities.** The traffic side of the barrier contains slots or holes, which connect with internal cavities and these, are often called Helmholtz resonators. Resonance occurs at selected frequencies depending upon the dimensions of the cavities, causing relatively high amplitude oscillations in the neck of the cavity, which causes a loss of energy through frictional damping. Fibrous or foam fillers can be included in the cavities to broaden the frequencies of the sound absorbed.

To be effective, any absorbing surface must provide good absorption at frequencies that are significant in highway traffic noise spectra and most often used in daily communication. The frequency spectrum of traffic noise is broadband, the highest sound levels occur at frequencies close to 1000 Hz. Normal conversation usually ranges from 250 to over 2000 Hz. For effective performance, therefore, traffic noise barriers should absorb strongly over a wide range of frequencies between 250 to 5000 Hz, which would result in a high NRC, this value is stated as a minimum of 0.8 from new FDOT guidelines [FDOT, 2003].

Criteria for Selecting Materials

In 1979, Menge and Powers [Menge, 1979] published the review criteria for selecting sound absorbing materials for use on highway noise barriers. Criteria for selecting sound absorbing materials included sound absorbing capacity, physical durability, acoustical durability, maintenance requirements and flame, fuel and smoke ratings. These criteria were:

1. **Sound absorbing capacity** – Only materials that meet the sound-absorbing criteria should be considered. For highway barriers, it is necessary to install on the barrier surfaces sound-absorbing treatments that have absorption coefficients of 0.6 or higher. Absorption

coefficients of at least 0.6 are necessary in the four most important octave bands for highway noise that makes up the NRC value: 250, 500, 1000, and 2000 Hz.

2. **Physical durability** – Materials that meet the first criterion should have sufficient durability. In the highway environment, they will be exposed to sun, water, wind, salt, air contaminants, and temperature changes. To remain effective, they must be able to resist these elemental forces for many years.
3. **Acoustical durability** – Materials that have sufficient physical durability must also resist degradation of their sound-absorbing properties. Oil and dirt can clog the tiny passages between the fibers that make up sound-absorbing materials. Clogging effectively inhibits the motion of air molecules, which is the mechanism by which sound is absorbed.
4. **Maintenance requirements** – If the sound-absorbing capacity of a material decreases as a result of clogging, the effectiveness of the barrier will decrease. Cleaning the barrier face may restore its acoustical performance, but requirements for maintenance should be avoided if possible. In addition, the appearance of sound-absorbing barriers should not deteriorate over time, and their finishes should not require cleaning or painting.
5. **Flame, fuel, and smoke ratings** – Materials that meet all of the above requirements should have flame, fuel, and smoke ratings that are low enough that they can be used safely beside highways.

Highway Barrier Absorptive Materials

The absorptive treatment materials listed below are those commercially available and have been successfully used and implemented in the United States for highway noise barriers. These absorptive treatment materials are u0sed when there is a need to mitigate degradation of acoustical performance due to sound reflections from both single and parallel noise barriers. There are many manufacturers offering sound absorptive treatment materials for outdoor use, however, many of them use similar materials as listed below. Some of the materials are proprietary and can only be purchased directly from the vendors. Often, there is a need for complex equipment to make these barriers, nonetheless, glass fiber and mineral wool sound absorptive systems can be installed by non-barrier suppliers instead of purchasing prefabricated products to save cost.

Glass Fiber

Glass fiber is a standard material for use in noise control. It is readily available. Its effectiveness as a sound-absorbing material has been extensively tested. Its durability and weathering characteristics have been observed over a period of several decades. Its cost, for most installations, is competitive with other available sound-absorbing materials.

Glass fiber varies in thickness from 2 in. to 4 in. when meeting the absorption criteria for highway use. Typical absorption coefficients of glass fiber are shown in Table 4. A protective facing and a support framework should contain the glass fiber. The reasons of using two types of protective facings for the glass fiber are: (1) perforated facing protects the fiber from physical abuse and (2) thin waterproof plastic or Mylar sheet protects the fibers from moisture, dirt, air contaminants, and air sifting (fibers floating out into the air).

Glass fiber is readily available in various densities, from 1 lb/ft^3 to 6 lb/ft^3. A 2-inch and 1.5 to 2 lb/ft^3 density glass fiber is the most efficient use of the material. An acoustically efficient installation would have 2-inch air space behind the glass fiber and a solid sound reflective surface behind the air space. A Mylar bag, 1-mil or 2-mil thick is a suitable wrapping material for the glass fiber for the exterior installation because it is not affected by ultraviolet light. Typical sound absorptive systems using fiber glass are manufactured by Industrial Acoustics Company, the product is called Noishield System.

Table 4: Typical Absorption Coefficients for Glass Fiber [Knauf, 2003]

Thickness	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC
2"	0.31	0.57	0.96	1.04*	1.03	1.03	0.9
2 ½"	0.43	0.82	1.12	1.07	1.04	1.03	1
3"	0.47	0.92	1.17	1.06	1.06	1.04	1.05

* Values greater than 1.0 can result from the test procedures, although not physically possible.

Mineral Wool

Physical and acoustical properties of mineral wool are very similar to glass fiber, it also has been used for decades as a sound absorptive treatment system on highway noise barriers. Mineral wool also needs protective facing to support and contain it. Typical absorption coefficients of mineral wool are shown in Table 5. Typical sound absorptive system using mineral wool is manufactured by Sound Fighter Systems (SF) and Empire Acoustic Systems.

Table 5: Typical Absorption Coefficients for Metal Wool [SF, 2003]

Thickness	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC
4"	1.08	1.16	1.11	1.03	0.9	0.68	1.05

Wood Fiber Planks

Wood fiber planks with proper installation are adequate sound absorbing materials for use on highway barriers. Wood fiber planks are made by fixing shredded wood fibers in a binder material. Typical absorption coefficients of wood fiber planks are shown in Table 6. The fibers are treated with fire-retardant substance; the binder can be hydraulic or Portland Concrete

Cement or a gypsum binder usually coated with silicone. Wood fiber planks are usually used as inexpensive form board for poured concrete slabs. A typical manufacturer using wood fiber planks as sound absorptive treatment system is The Fanwall Corporation with the product named Durisol.

Table 6: Typical Absorption Coefficients for Wood Fiber Planks [Fanwall, 1989]

Thickness	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC
2"	0.09	0.26	0.72	0.87	0.88	0.87	0.70
3 ½"	0.18	0.48	0.97	1.94	0.96	0.94	0.85

Cementitious Materials

Cementitious materials may be sprayed onto a backing or may be poured and wet cast during the precast production and is integrated with the structural portion of the panel. Spray-on cementitous materials must be thick enough to provide the needed NRC. Pour and wet cast cementitous materials with thickness 2.5 inches to 3.5 inches can provide an excellent NRC. Typical absorption coefficients of cementitous material are shown in Table 7. Concrete Solutions, Inc is the typical manufacturer of this material as sound absorptive system; their product is called SoundSorb which has NRC as shown Table 7 and is claimed to be durable and cost effective.

Table 7: Typical Absorption Coefficients for Cementitous Materials [CSI, 2003]

Thickness	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC
2.5"				NA			0.85
3.0”	0.23	0.60	1.25	0.97	0.95	0.96	0.95
3 ½"				NA			1.0

Resonant Cavities

Structures containing resonant cavities can be designed to meet the acoustic criteria for sound absorbing highway barriers as was discussed previously in this work. Resonant cavities may have many different forms. They can be a single cavity with a single slot or neck opening; a Helmholtz resonator, or, an air space divided into "honeycomb" compartments behind a perforated sheet of material such that multiple perforations open into each compartment.

Helmholtz resonator has a very narrow frequency band where absorption takes place and as such its use is somewhat limited, however, when fibrous fillers are inserted into the cavities, the sound absorption at higher frequencies is generally improved. Helmholtz resonator is commercially available in the form of concrete blocks with slots in their front faces or called sound absorbing concrete masonry units. Proudfoot Company, Inc has developed its sound absorbing concrete masonry units called SoundBlox using concrete block. This product has the same compressive strength as standard hollow concrete masonry units of similar composition. Typical absorption coefficients of sound absorbing concrete masonry are shown in Table 8.

Table 8: Typical Absorption Coefficients for Sound Absorbing Concrete Masonry [Proudfoot, 2003]

Thickness	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC
4"	0.18	0.64	1.02	0.72	0.8	0.58	0.8
6"	0.48	1.14	0.91	0.76	0.67	0.51	0.85
8"	0.48	0.99	0.98	0.58	0.7	0.64	0.8
12"	0.57	0.76	1.09	0.94	0.54	0.59	0.85

The "Honeycomb" product can be further improved and filled with absorptive material to improve its sound absorption capability. A local manufacturer, Acoustic Fab, Inc. in Stanford, FL has patented a new honeycomb product with absorptive material (Acousti-*Flo* Panel **AF1.4**). This product has a high performance hybrid structure that combines acoustic absorption and sound barrier properties with structural strength and rigidity. It is also low weight and resistance to corrosion, elevated temperatures, moisture and fire.

Table 9: Typical Absorption Coefficients for honeycomb product [Acoustic Fab, 2003]

Thickness	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC
2"	0.12	0.34	0.67	0.94	0.96	0.81	0.73
4"	0.28	0.63	0.95	0.98	0.88	0.75	0.86

Durability of Sound Absorbing Materials for Highway Noise Barriers

Behar and May of Canada studied through field exposure and laboratory tests two properties of sound absorbing materials intended for highway noise barrier applications: their durability and their sound absorption coefficients before and after exposure to adverse weather [Behar, 1980]. After surveying the products of 34 manufacturers, eight materials and one "absorbing system" were selected for the tests. Table 10 presents description of these items.

Tests included:

1. Attachment for 9 months (including the winter season) to a wooden noise barrier erected just behind the guide rail of the Queensway freeway in Ottawa
2. Measurement of sound absorbing coefficients before and after these tests
3. Freezing and thawing (total and partial submersion)
4. Accelerated weathering
5. Salt spray exposure

Behar and May also pointed out that the freeze-thaw cycle tests were done with the barrier material immersed in water, which may constitute an extremely harsh and not entirely representative test environment. They further recommended that the results be treated with caution and only viewed as resource material for decision making. Table 11 provides an overall summary of the results as presented in their report.

Table 10: Description of the Materials and Absorbing System

Material or system no.	Description
1	Low density cellular glass, not containing organic binders. Supplied in 0.3 m × 0.46 m (12 in × 18 in) and 0.46 m × 0.61 m (18 in × 24 in) units in both 0.05 m and 0.10 m (2 in × 4 in) thicknesses.
2	Lightweight building material, made of chemically mineralized and neutralized organic softwood shavings, bonded together under pressure with Portland cement. It is normally supplied with a hard backing, consisting of 30 mm (1.18 in) thick concrete. All tests were done without the backing.
3	Sound absorption system consisting of aluminum cage, enclosing glass wool boards, wrapped in polyethylene.
4	Glass fibers bonded in a thermosetting resin.
5	Same as 4, protected by glass cloth.
6	Chemically treated long northern aspen wood fibers bonded with Portland cement, molded under pressure.
7	Homogeneous, 100% recycled, all wood fiber material, processed with moisture resistant ingredients, compressed into a high density structural panel.
8	Flexible polyurethane foam.
9	Porous, random textured material made of polyester resin, glass fibers, aggregates and filters.

Table 11: Overall Summary of Tests and Results

Material		Tests and results							
No.	Description	Highway exposure (9 months)	Sound absorption	Change in sound absorption after highway exposure	Total immersion	Partial immersion	Accelerated weathering	Salt spray exposure
1	Low density cellular glass	Very fragile, fell apart during installation	Not tested	Not tested	Not tested	Not tested	Not tested	Not tested
2	Wood shavings bonded with Portland cement	Little loss of material, more severe on the lower part of the sample	Good (NRC = 0.55)	None	Disintegrated	Swelled up 50 mm above the water level	Adhesive properties of the cement destroyed	No reaction to salt
3	Aluminum cage enclosing glass wool wrapped in polyethylene	Visually undamaged	Not tested	Not tested	Not tested	Not tested	Not tested	Not tested
4	Glass fiber bonded in a thermosetting resin	Good	Good (NRC = 0.55)	None	Forms a mass of loose fiber	Forms a mass of loose fiber	Losses rigidity and forms a mass of glass fiber	Losses rigidity and forms a mass of glass fiber
5	Same as 4, protected by glass cloth	Visually undamaged	Not tested	Not tested	Not tested	Not tested	Not tested	Not tested
6	Wood fiber bonded with Portland cement	Visually undamaged	Fair (NRC = 0.35)	None	Softened and swelled	Softened and swelled up to 50 mm above water level	Adhesive properties of the cement destroyed	Not reaction t salt
7	Wood fiber material compressed into a high density structural panel	Visually undamaged	Poor (NRC = 0.15)	None	Softened and swelled	Softened and swelled up to 75 mm above water level	Delaminated completely	Delaminated completely
8	Flexible polyurethane foam	Visually undamaged	Fair (0.35)	None	Undamaged	Undamaged	Surface degradation and 50% thickness shrinkage	Not reaction to salt
9	Random textured glass fiber and polyester resin	Visually undamaged	Good (NRC = 0.40)	None	Undamaged	Undamaged	Undamaged	Undamaged

Basis for ratings: excellent NRC ≥0.80; very good NRC 0.6-0.75; good NRC 0.40-0.55; fair NRC 0.20-0.35.

Effect of Long-term Exposure on the Acoustical Performance of Porous Sound Absorbing Materials

This study by Myles, Ver and Henderson was part of a research project for the NASA Langley Research Center to design an outdoor anechoic test apparatus [Myles, 1976]. Nine sample anechoic chamber wedges representing six materials were left undisturbed for eleven months, starting in August 1973. Six absorption impedance tube tests were made, and each wedge was inspected after exposure for damage.

The researchers concluded that all of the materials except the polyester non-reticulated (sample 3) showed little or no deterioration or loss of acoustical performance. Sample 3 became brittle on the surface, and showed considerable loss of volume and reduced sound absorption.

Table 12: Physical Characteristics of the Material Tested [Myles, 1976]

Sample	Material	Density (lb/ft^3)
1	Polyester non-reticulated foam with fire retarded treated	2.0
2	Polyester non-reticulated foam	2.0
3	Polyester non-reticulated foam	1.5
4	Fiber glass covered with ¼” mesh hardware cloth	2.25
5	Fiber glass covered with ¼” mesh hardware cloth	3.0
6	Fiber glass covered with ¼” mesh hardware cloth	4.25

Research in the United States

Pejaver and Shadley – Multiple Reflections between Parallel Noise Barriers

Pejaver and Shadley did a very important study on the effects on receivers outside the parallel barrier canyon theoretically and with point source scale modeling in 1976 [Pejaver 1976]. Using geometrical acoustics, they predicted the degradation in the performance of a single traffic noise barrier due to the presence of a second barrier on the opposite side of the highway. Their work included several assumptions:

1. Point source in center of canyon at height of 8 ft (2.4 m)
2. Equal wall height
3. Same absorption coefficient for each wall
4. Use of absorption coefficients
5. No scattering

The researchers performed limited point source scale model testing to check on their mathematical model. Figure 9 shows degradation for point source scale modeling simulating a 72 ft (21.9 m) wide canyon with 15 ft (4.6 m) walls and a source-receiver distance of 100 ft (30.2 m). Of note is the width to height ratio of 4.8, which is represents a narrow cross section. Degradation ranged from 3 to 6 dB(A) for NRC = 0.05 (reflective wall) and 2.5 to 4.5 dB(A) for NRC = 0.2 (slightly absorptive wall), in both cases increasing with increasing height. Agreement with calculations was within ± 0.5 dB(A) for receivers with no view of the source of the far wall.

As can be seen in Figure 9, poor agreement was indicated at the highest receiver point. At this location, the receiver could not see the source, but could see the far wall. The mathematical model showed a decrease in degradation in this region as receiver height increased, while their measurements indicated an increase in degradation, continuing the trend from the lower height receivers.

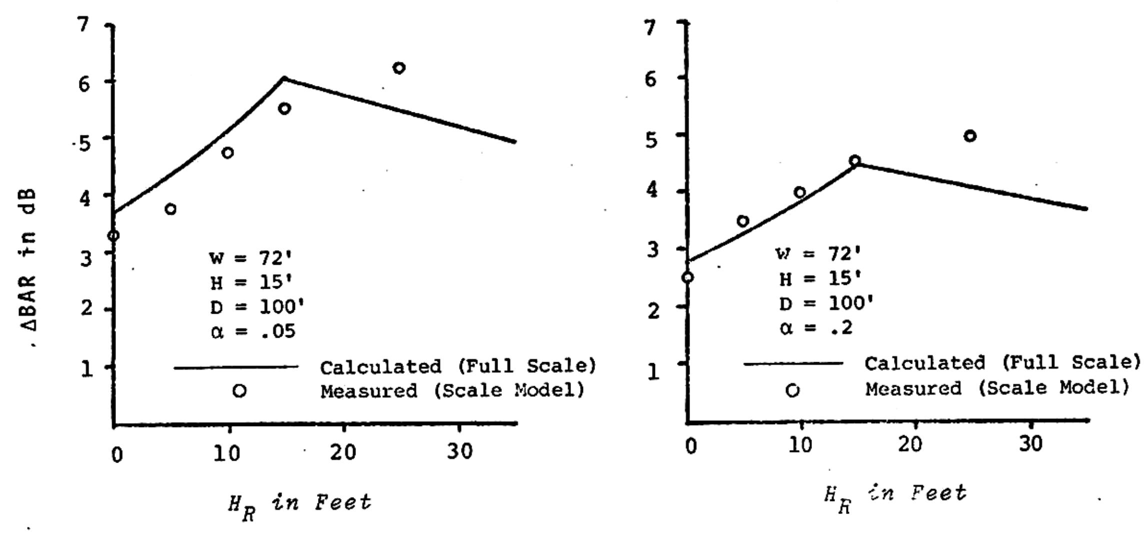


Figure 9: Parallel Measured versus Calculated Parallel Barrier Degradation as a Function of Absorption Coefficient. [Pejaver, 1976]

The researchers also made a line source calculation of parallel barrier insertion loss degradation for several canyon widths and barrier heights. Figure 10 presents degradation as a function of receiver height for four scenarios. As may be seen, degradations of as much as 12 dB(A) were computed as sound levels from not just the cross section, but the entire roadway were considered.

Perjaver and Shadley conclusions were:

1. The degradation in single wall performance due to parallel barriers can be as much as 12 to 13 dB(A) (the received level can actually be higher than the free-field (no barrier) level)
2. The depressed roadway cross-section was most sensitive to degradation
3. Absorptive treatment provided substantial improvement
4. Degradation increased as receiver distance increased, as canyon widths decreased and as barrier heights increased
5. Ground reflections could be ignored when more than ten wall reflections affect the level at receiver
6. Geometrical acoustics was workable and straightforward.

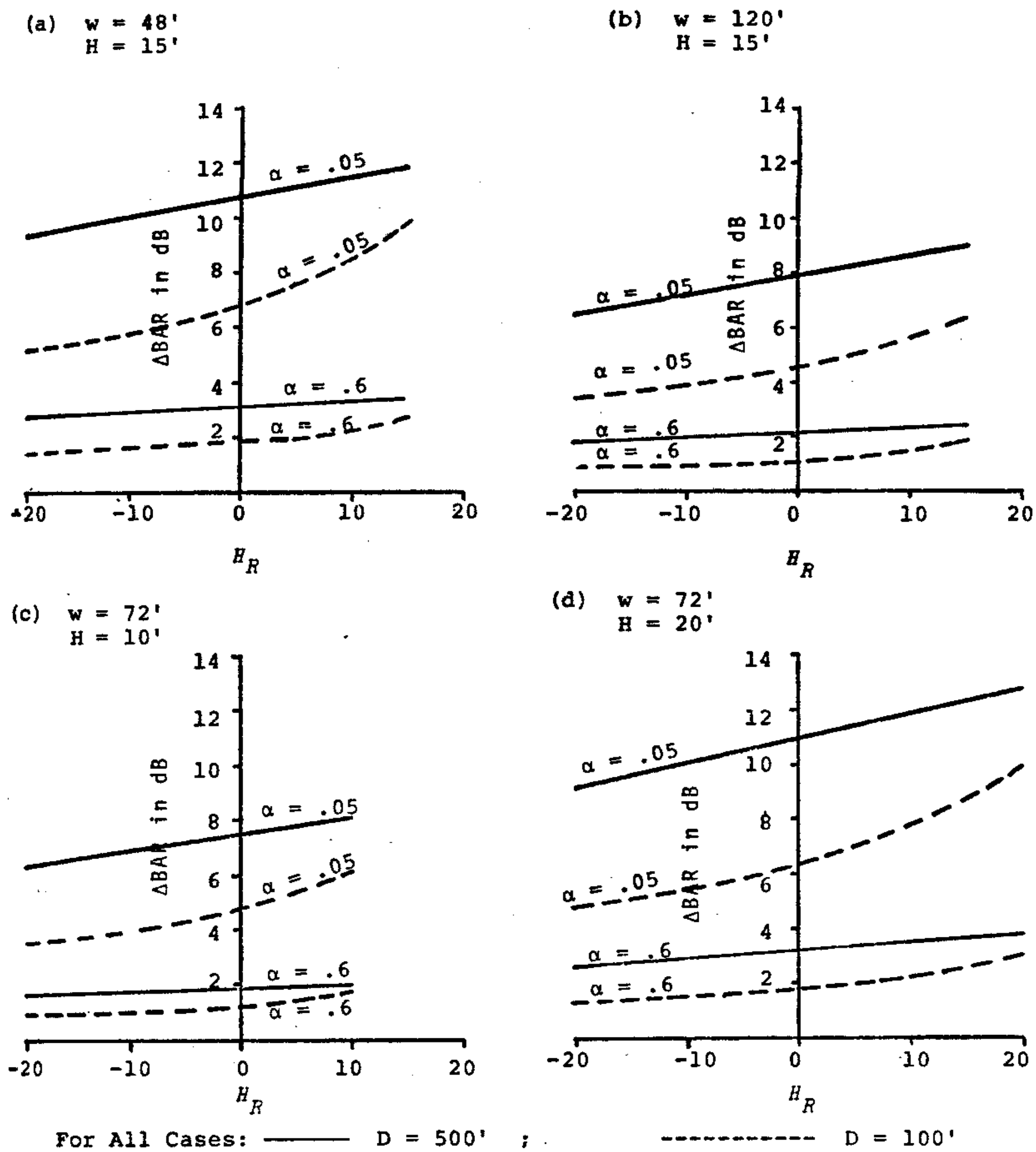


Figure 10: Calculated Parallel Barrier Degradation for Several Barrier Height and Canyon Width (H_R is Receiver Height) [Pejaver, 1976]

Simpson – Parallel Barrier Nomograph

Simpson developed a parallel barrier insertion loss degradation nomograph based on the Pejaver/Shadley assumptions and results [Simpson, 1976]. This nomograph is contained in the FHWA Noise Barrier Design Handbook. The nomograph, as shown in Figure 11, permits determination of the reduction in single noise barrier performance due to the addition of an opposing parallel equal height barrier. Input data for the nomograph include horizontal distance D_B between the barrier and the receiver, the separation distance W between barriers, the receiver height H_R, the attenuation Δ_B provided by the nearby barrier for a ground level observer, and NRC. Examples of the use of the parallel barrier nomograph are also presented in the handbook. In the example, for receivers at 5 and 16 ft above the ground, the barrier attenuation has been degraded by 4.5 and 6.5 dB(A) for a reflective barrier; for the same case with NRC of 0.8, the degradation in barrier performance is less than 1 dB(A) for both receivers.

Menge – Inclined and Absorptive Parallel Noise Barriers

Menge [Menge, 1980] studied inclined and absorptive parallel highway noise barriers with scale modeling. As illustrated in Figure 12, for 16 ft (4.9 m) high vertical walls, he showed an insertion loss of 4 dB(A) at 500 Hz for reflective walls and 11.5 dB(A) for absorptive walls. For 18 ft (5.5 m) walls, the insertion losses were 5 dB(A) and 13.5 dB(A) for the two cases. Thus, multiple reflection effects of 7.5 to 8.5 dB(A) were largely reduced by the use of sound absorptive treatment. When the walls were inclined outward by 10 degrees, the insertions were about 10 dB for both 4.9 m cases and about 12 dB(A) for both 5.5 m cases, showing that wall inclination can also be effective.

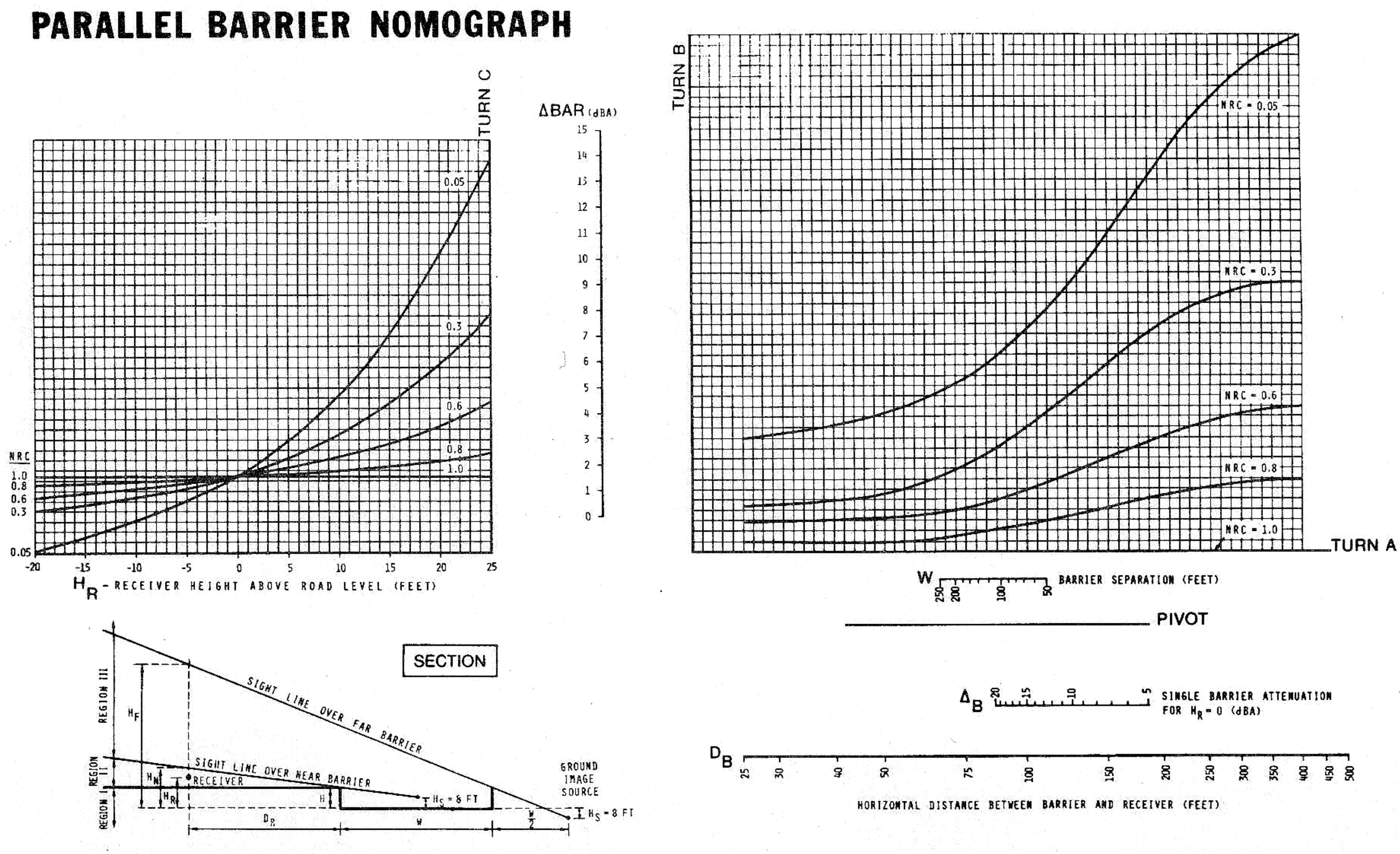


Figure 11: Parallel Barrier Nomograph [Simpson, 1976]

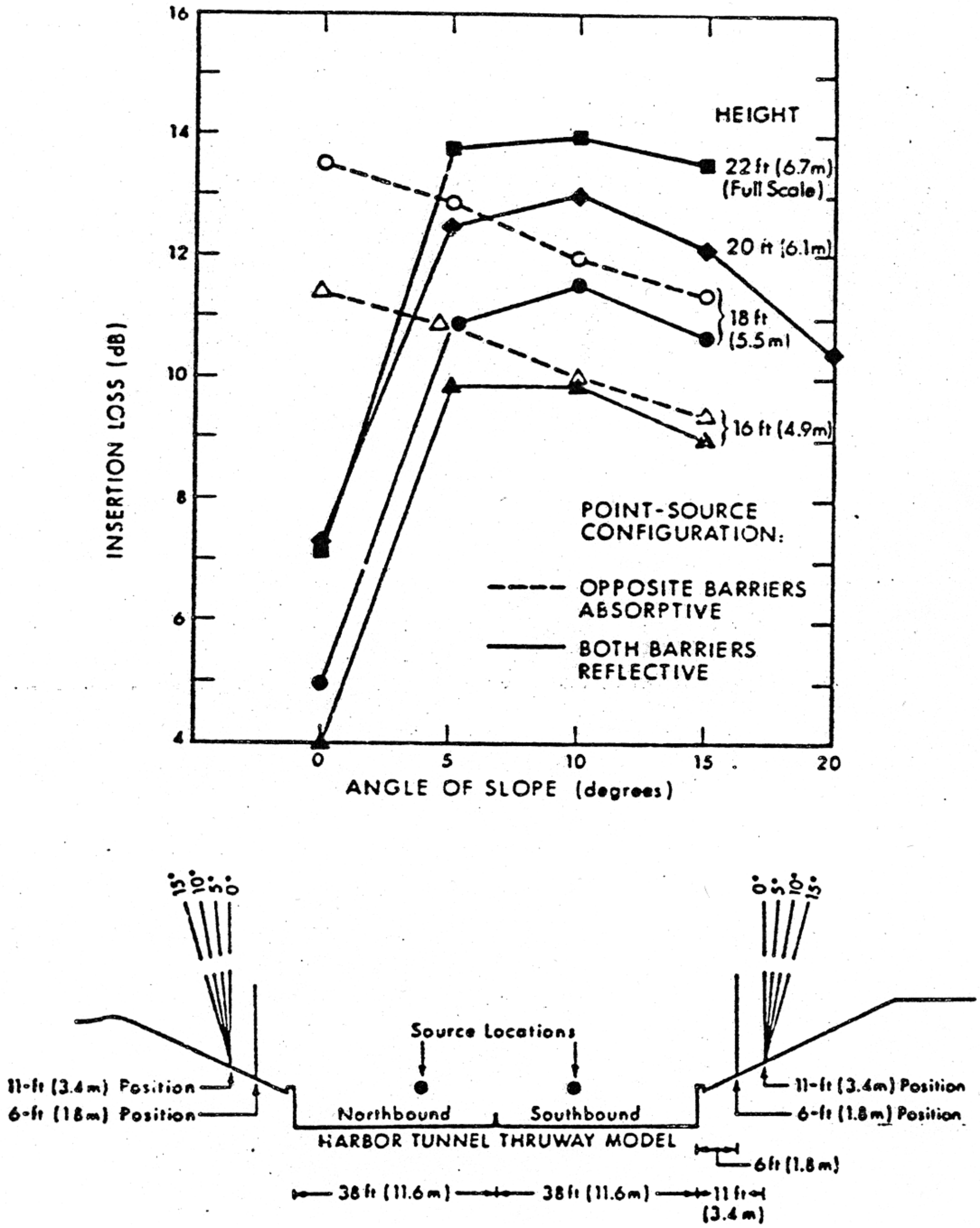


Figure 12: Insertion loss as a function of angle of slope of barrier for absorptive (---) and reflective (–) barriers of heights between 4.9 m and 6.7 m [Menge, 1980]

Bowlby and Cohn – Sound Absorptive Highway Noise Barrier

Bowlby and Cohn carried out a large analysis in the US of the need for sound absorptive treatment on highway noise barriers on the Interstate 440 project in Nashville, Tennessee. The resultant design included nearly ½ miles of sound absorptive barriers. A computer program called IMAGE-3 was developed to study the multiple reflections effect and the design and effectiveness of using absorptive treatment [Bowlby, 1984].The algorithm of the Image-3 considers noise contributions to receptors outside the highway canyon from three types of vehicular noise sources (automobiles, medium trucks, and heavy trucks) traveling along a line within a canyon. It incorporates the basic emission, propagation, and diffraction algorithms in the older FHWA highway traffic noise prediction model, STAMINA2.0 [Bowlby, 1984]. In addition, it uses ray-tracing acoustic algorithms as shown in Figure 13 to generate image sources and absorption coefficients to reduce the intensity of each reflection.

The final form of the algorithm represents a restatement of the basic equation of the FHWA model, a term added for absorption on each reflection, and the use of image sources. The L_{eq} contribution at a receiver from the i^{th} image source [$(L_{eq})_i$] for a particular vehicle type on a roadway is:

$$(L_{eq})_i = 10\log\left\{0.4735\left[\frac{V \cdot \Delta\phi}{S \cdot d_i}\right] \times 10^{(\overline{L_o})_E/10} \times \left[\prod_{i=1}^{m}\left(1-\alpha_j\right)\right]\right\} - \Delta_B \qquad (6)$$

where V = hourly volume of this vehicle type (vehicle/hr)
$\Delta\phi$ = angle (in radians) at the receiver subtended by the endpoints of the image roadway; if $\Delta\phi$ is in degrees, the coefficient 0.4735 would be 0.008234
S = travel speed of the vehicles (mph)
d_i = normal distance from the receiver to the i^{th} image roadway (ft)
$\left(\overline{L_0}\right)_E$ = reference energy mean emission level for this vehicle type (dB)

α_j = absorption coefficient to be applied to the jth reflection for the ith image source
Δ_B = barrier attenuation for the ith image roadway (dB)

Note that the product expression $\left[\prod_{j=1}^{m}\left(1-\alpha_j\right)\right]$ indicates the intensity of the image source is reduced by the factor (1-α_j) for each reflection that occurs in the propagation of the sound of this image (for j ranging from 1 to m).

The method of locating the image source is calculated by using Equation 7, where the distance to the image is a function of the actual source receiver distance, the width of the canyon, and the wall off which the sound first reflects.

$$d_i = d_{br} + i(w_1 + w_2) + \begin{cases} w_2 \; if \; i \; is \; odd \\ w_1 \; if \; i \; is \; even \end{cases} \tag{7}$$

where d_{br} = distance from the receiver to the near wall
w_1 = distance from the source to the near wall
w_2 = distance from the source to the far wall
i = sequential number of this image, where i = 0 is the direct source, i = 1 is the image, and so on

Once all of the image contributions have been computed for a particular vehicle type, the total L_{eq} is computed as follows:

$$\left(L_{eq}\right)_{total} = 10\log\left\{10^{\left(L_{wq}\right)_{direct}/10} + \sum_{i=1}^{n}\left[10^{\left(L_{eq}\right)_i/10}\right]\right\} \tag{8}$$

where $(L_{eq})_{direct}$ = L_{eq} contribution from the actual source
$(L_{eq})_i$ = L_{eq} contribution from the ith image

The vehicle type L_{eq} values are then combined to determine the roadway total L_{eq} contributions at the receiver.

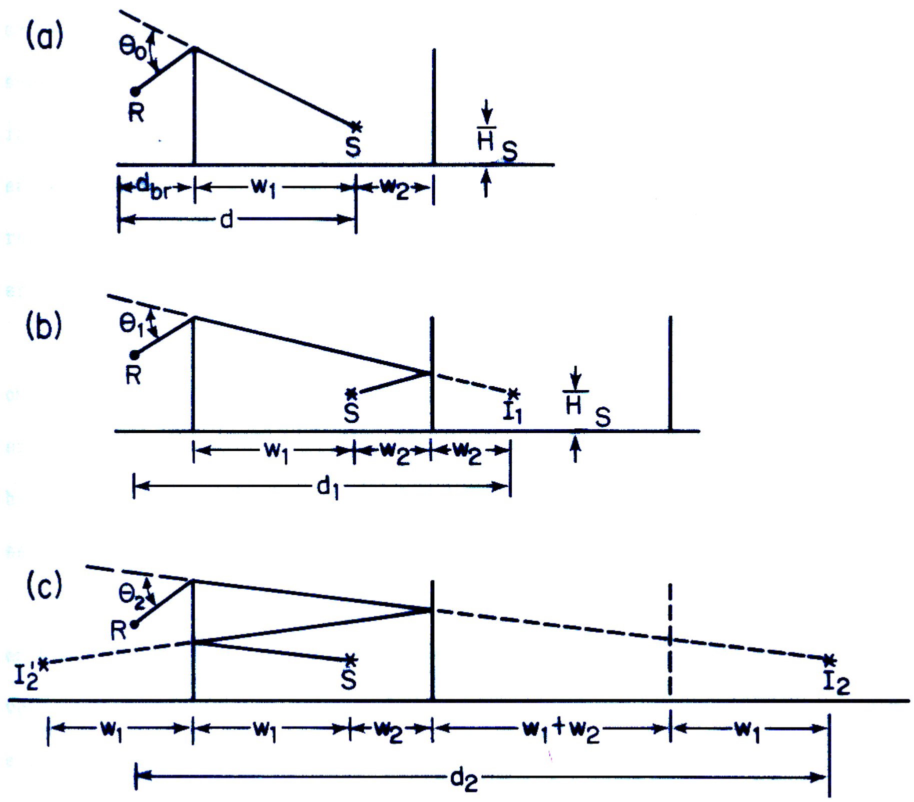


Figure 13: Parallel barrier cross section showing (a) actual source (S) ray diffracting over near wall; (b) first image source (I_1); and (c) second image (I_2), which is an image of image source I_2' [Bowlby, 1986]

By using the program, a set of graphs (Figure 14) was generated to show the insertion loss degradation as a function of barrier height and the absorption coefficient for automobiles and trucks at various receiver distances with a canyon width of 120 ft (36.6 m) for the 6-lane at grade highway.

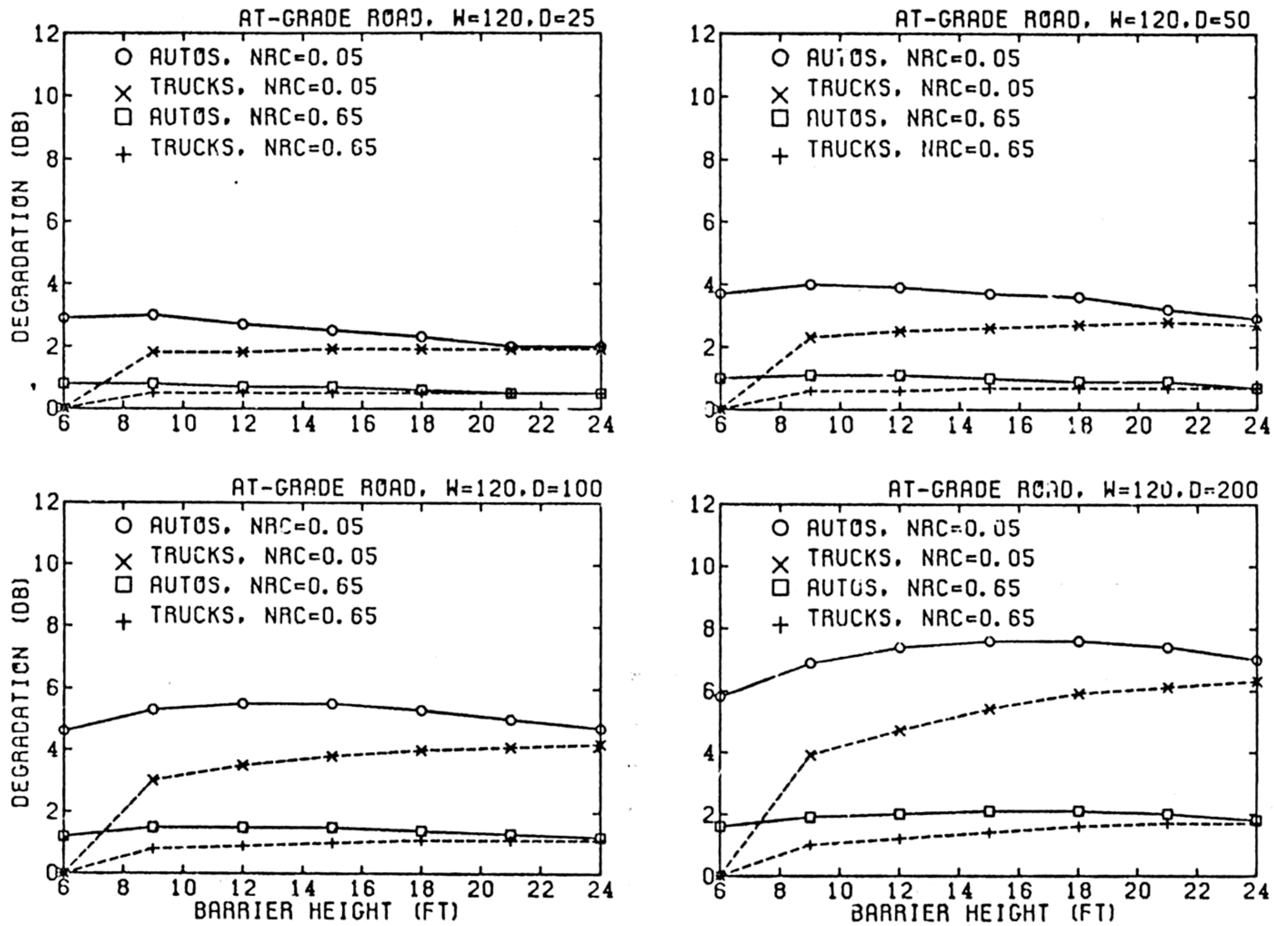


Figure 14: Parallel Barrier Insertion Loss Degradation as a function of Barrier Height for an "At-grade" Scenario with Canyon Width of 120 ft (36.6 m) [Bowlby, 86]

Flemming and Rickley – Dulles Airport Project

Flemming and Rickley, with the support of Vanderbilt University (Bowlby, Wayson, and Greenwood), conducted an experimental highway noise barrier constructed at Dulles International Airport [Flemming, 1989]. The study site contained two experimental highway noise barriers constructed in parallel on opposite sides of a two-lane asphalt service road. The barrier site contained a 500-foot long, 14-foot high barrier and a 250-foot long, 14-foot high barrier. The barriers were 87 feet apart, which resulted in a maximum width-to-height ratio of 6.2. The barriers were unique in that they could be configured to have absorptive and/ or reflective roadside facades, or be independently tilted outward, away form the roadway, at angles of 7, 15, and 90 degrees. The barrier configurations tested are shown in Table 13. Measurements were conducted with both controlled moving point sources (trucks) and an artificial fixed-point source (speakers system). Some of their findings are summarized as below:

1. An insertion loss degradation as large as 6 dB(A) was measured for the parallel reflective barriers tested.
2. The addition of absorptive treatment to the roadside façade of two vertical reflective highway noise barriers improved their performance by 2 to 6 dB(A).
3. Tilting the barriers outward was equally effective at eliminating the multiple reflections when compared with the application of acoustically absorptive treatment.
4. Add the width to height ratio finding

Table 13: Barrier Configurations and Test Dates for Dulles Noise Barrier Project – 1989 [Flemming, 1989].

Date	Barrier Configuration	500-foot Barrier		250-foot Barrier		Notes
		Surface	Tilt	Surface	Tilt	
05/25/89	1	Absorb.	0	Absorb.	90	
06/27/89	2	Absorb.	0	Absorb.	0	
		Absorb.	0	Absorb.	0	Special Art. Source
06/28/89	3	Absorb.	0	Absorb.	7	Incomplete Art. Source
06/29/89	4	Absorb.	0	Absorb.	15	
07/12/89	5	Absorb.	15	Absorb.	15	
07/24/89	6	Absorb.	7	Absorb.	7	
07/26/89	7	Absorb.	0	Absorb.	7	No Art. Source
08/01/89	8	Reflec.	0	Reflec.	15	
08/02/89	9	Reflec.	0	Reflec.	0	
08/08/89	10	Reflec.	0	Reflec.	7	No. Art. Source
08/09/89	11	Reflec.	7	Reflec.	7	
08/15/89	12	Reflec.	15	Reflec.	15	

Hendriks – Field Evaluation of Acoustical Performance of Parallel Highway Noise Barrier in California

Hendriks has made extensive field measurements of noise, traffic, and meteorology in three stages to investigate the effects of multiple noise reflections between two parallel masonry sound walls on the acoustic performance of one of the sound walls [Hendriks, 1992]:

- Stage 1 - Before barrier construction,
- Stage 2 - After construction of the near barrier
- Stage 3 - After construction of the barrier on the opposite side of a highway

The selected site was a typical of many parallel barrier configurations in California. A total of 105 uncontaminated runs were made: 27 during Stage 1, 45 during Stage 2, and 33 during Stage 3. Each run consisted of the 11 simultaneous noise levels recorded from the microphones. Noise measurements for Stages 1, 2, and 3 were normalized for differences in traffic via a primary control microphone in a location that was not influenced acoustically by the sound walls.

Hendriks found that the mean insertion loss degradation due to 2 parallel noise barriers (as shown in Figure 15) ranged from 0 to 1.4 dB(A), which is less than can be perceived by normal ears. The author also suspected that this amount of degradation occurs when the ratio of the separation distance and height of the barriers is higher than 10:1 as reported by previous research that will be discussed next.

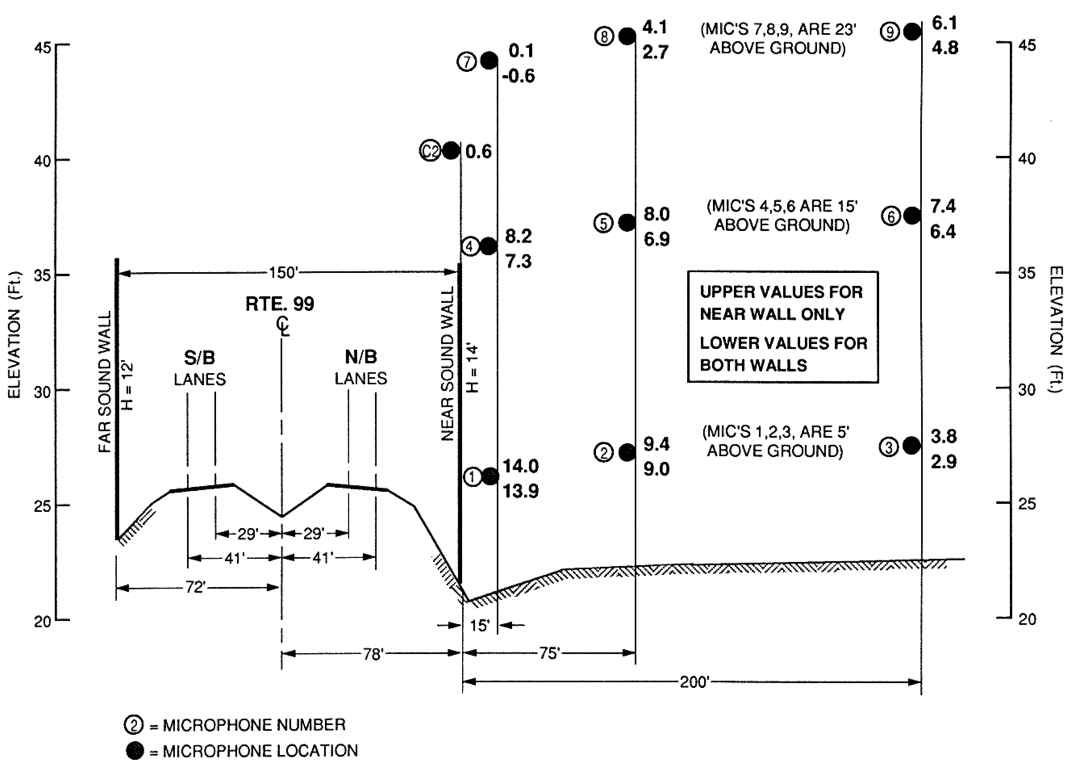


Figure 15: Mean Insertion Loss for Near Wall only and for Both Walls (Route 99 in South Sacramento [Hendriks, 1992].

Flemming and Rickley – Montgomery County Project

Flemming and Rickley also made field measurements at a highway noise barrier site located along Interstate 495 in Montgomery County, Maryland [Flemming, 1992]. The project was sponsored by FHWA. The objective of this project was to measure the degradation in acoustic performance of a highway noise barrier due to the close proximity of a parallel barrier on the opposite site of the roadway under free flowing traffic conditions. The site configuration and the measured mean insertion loss can be seen in Figure 16. Both barriers were 18.8 ft and approximately 164 ft apart for a width-to-height ratio of 8.8. The researchers found that the mean barrier insertion loss degradation due to multiple reflections between the parallel barriers ranged from 0.6 to 2.8 dB(A) depending on microphone height and offset distance behind the barrier. Based on the data from this study and 2 other projects (Table 14), they recommended that the separation distance to barrier height ratio (W/H) of 10:1 was necessary to avoid a perceptible degradation in barrier insertion loss.

Table 14: Comparison of W/H Ratios and Maximum Δ_{IL} [Fleming, 1992]

Project	W/H	Max. Δ_{IL} (dBA)	Mic. Height/Offset (ft)*
Dulles Study	6:1	6.2	+16/88
This Study	8.8:1	2.8	+13/131
Caltrans Study	15:1	1.4	+10/75, +10/200

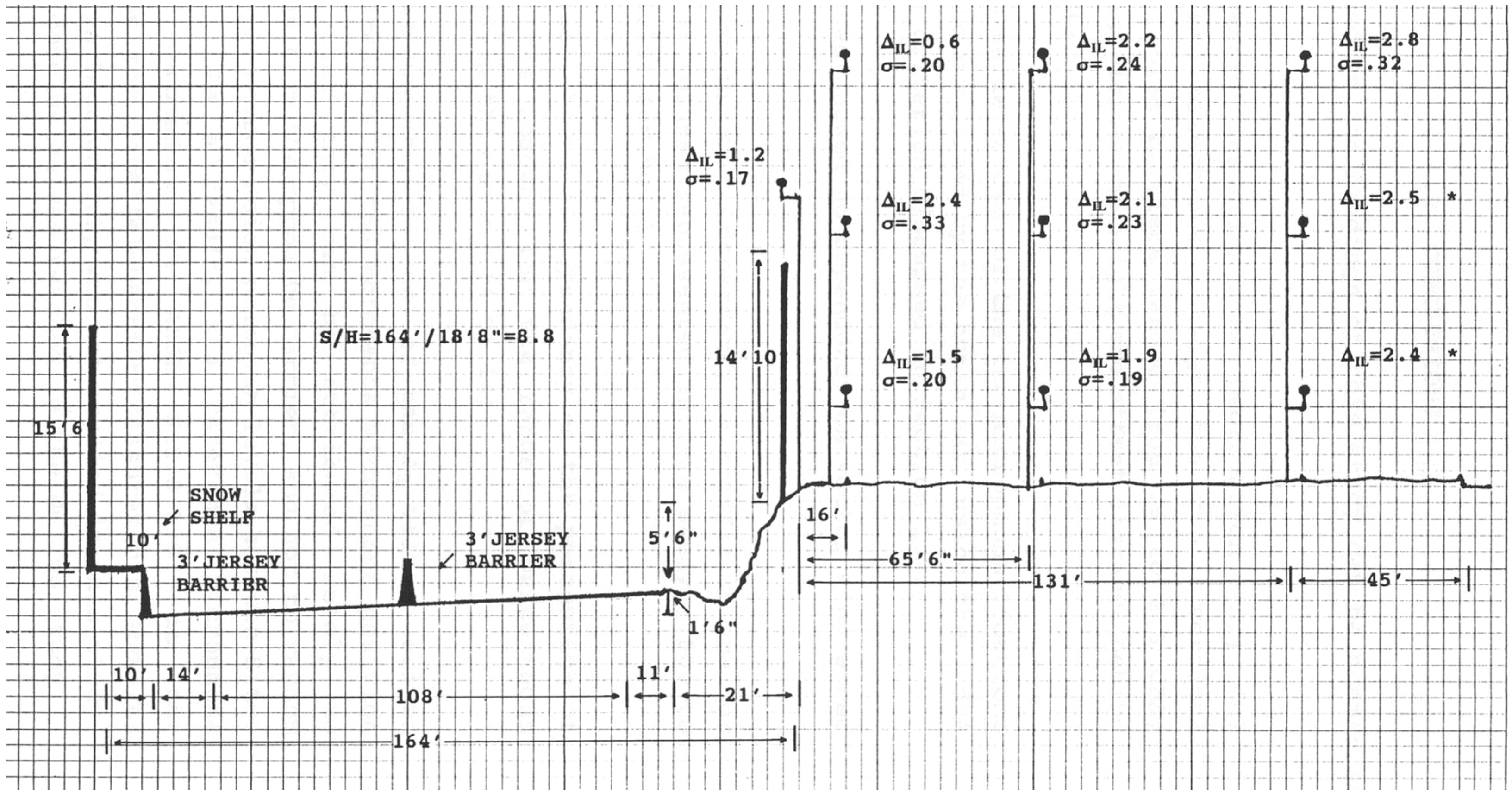
*Microphone height in feet, relative to the top of the barrier, and microphone offset in fee behind the barrier.

Flemming and Rickley – Performance Evaluation of Experimental Highway Noise Barriers

Flemming and Rickley's research from the Dulles Airport and Montgomery County led to the new guideline for parallel barrier as in Table 15 [Fleming, 1994]. It was determined that the W/H ratio is inversely proportional to the degradation and this can be attributed to: (1) the decrease in the number of reflections between the barriers; and (2) the weakening of the reflections due to geometrical spreading and atmospheric absorption. They recommended that this rule-of-thumb (W/H ratio) can be used by State transportation agencies to categorize parallel barrier sites based on the W/H ratio and this methodology could potentially result in significant cost savings to them.

Table 15: Guideline for Categorizing Parallel Barrier Sites Based On The W/H Ratio**.**

W/H Ratio	Maximum Δ_{IL} in dB(A)	Recommendation
Less than 10:1	3 or greater	Action required to minimize degradation.
10:1 to 20:1	0 to 3	At most, degradation barely perceptible; no action required in most instances.
Greater than 20:1	No measurable degradation	No action required.



***Adjusted L_{eq} – excluding noise data easily identified as emanating from vehicle pass-bys on Forest Glen Road.**

Figure 16: Mean Insertion Loss Degradation, Δ_{IL} (dBA) of Maryland I495 Barrier Test Site [Flemming, 1992]

Research from Other Countries

May and Osman – Scale Modeling of Parallel Highway Noise Barriers

May and Osman of Canada evaluated different barrier shapes using a point source scale modeling technique [May, 1980]. The study included three scenarios: single barrier between highway and receiver; single barrier on the opposite side of the highway from a receiver, and the parallel barrier on each site of the highway. For the parallel barrier situation, both four and six lane highways were examined. Each highway had four shoulders and a median, as shown in Figure 17. In each case, a source was located on the nearest lane to the receivers, and a second source was located on the first lane beyond the median.

The cross-sectional shapes that were studied included: thin screen, wide top, T-, Y- and arrow-profiles, inclined wall and cylindrical topped wall. Thin screen barrier is a thin vertical barrier with knife-edge top; wide top barrier is a vertical thick barrier; T-profile barrier is a vertical base barrier with horizontal cap; Y-profile barrier is a vertical base barrier with angled-up top on each side; arrow-profile barrier is a vertical base barrier with angled-down top on each side; inclined wall is the barrier with angled back from the sound source; and cylindrical topped wall is a vertical base barrier with cylindrical top .

The scale model results, presented in Table 16, showed parallel barrier degradations of 1 to 2 dB(A) from the near-lane source and up to 6.2 dB(A) for the far-lane source. When the absorptive treatment was applied to all walls (NRC of 0.74), the degradation was negative or minimal for the near-lane source but still as much as 4.9 dB(A) for the far-lane source. Thus, absorption appeared to reduce degradation by about 2 to 3 dB(A). The authors indicated that degradation appeared to increase with increasing receiver distance from the barrier for both the absorptive and reflective cases.

For the single barrier case (Figure 18), the authors compared the predicted and measured point source (Table 17 and Table 18) sound pressure levels and found that both sets of data agreed closely for the reflective barrier. This allowed them to predict the line source with some confidence that the measured sound pressure level would closely agree with predicted values. The researchers therefore concluded that a noise increase occurs on the unprotected side of the highway when a reflective noise barrier is installed and the increase is about 1 dB(A) at 15 m (50 ft) from edge of pavement, rising to 2 dB(A) at 60 m (200 ft).

Table 16: Point Source Parallel Barrier Insertion Loss Degradation [May, 1980].

No. of Lanes	Receiver/ Wall Distance (m)	Receiver Height (m)	Insertion Loss Degradation (dBA)			
			Reflective Walls		Absorptive Walls	
			Near Lane Source	Far Lane Source	Near Lane Source	Far Lane Source
4	16.2	1.2	0.5	3.5	-3.0	1.5
	32.2	1.2	2.5	4.0	-1.5	1.5
	32.2	2.0	2.0	6.0	-2.0	4.0
	32.2	4.0	2.0	6.0	-0.5	3.5
	32.2	6.1	3.0	6.0	0.5	3.0
	40.5	1.2	3.5	6.0	-1.5	2.5
6	16.2	1.2	0.6	4.2	0.0	2.5
	32.2	1.2	0.9	3.9	-1.2	2.5
	32.2	2.0	1.2	6.2	-0.2	4.9
	32.2	4.0	1.5	5.5	0.4	3.4
	32.2	6.1	1.7	4.4	1.8	2.8
	40.5	1.2	1.7	5.5	0.0	0.8

Table 17: Predicted Sound Level Increments on The Unprotected Side of The Highway When A Single Conventional Barrier Is Installed [May, 1980].

Type of source	Receiver distance from edge of pavement [m(ft)] 15 (50)	30 (100)	61 (200)
	Predicted sound level increments (dB(A))		
Point	0.5	0.9	1.4
Line	1.1	1.6	1.9

Table 18: Measured Sound Level Increments on The Unprotected Side of The Highway When Single Barriers of The Types Are Installed; For Point Sources [May, 1980].

Type of barrier	Receiver distance from edge of pavement [m(ft)] 15 (50)	30 (100)	61 (200)
	Measured sound level increments (dB(A))		
Conventional	0.5	0.7	1.3
Conventional absorptive side*	0	0.2	0.5

* NRC of absorptive material used was 0.74

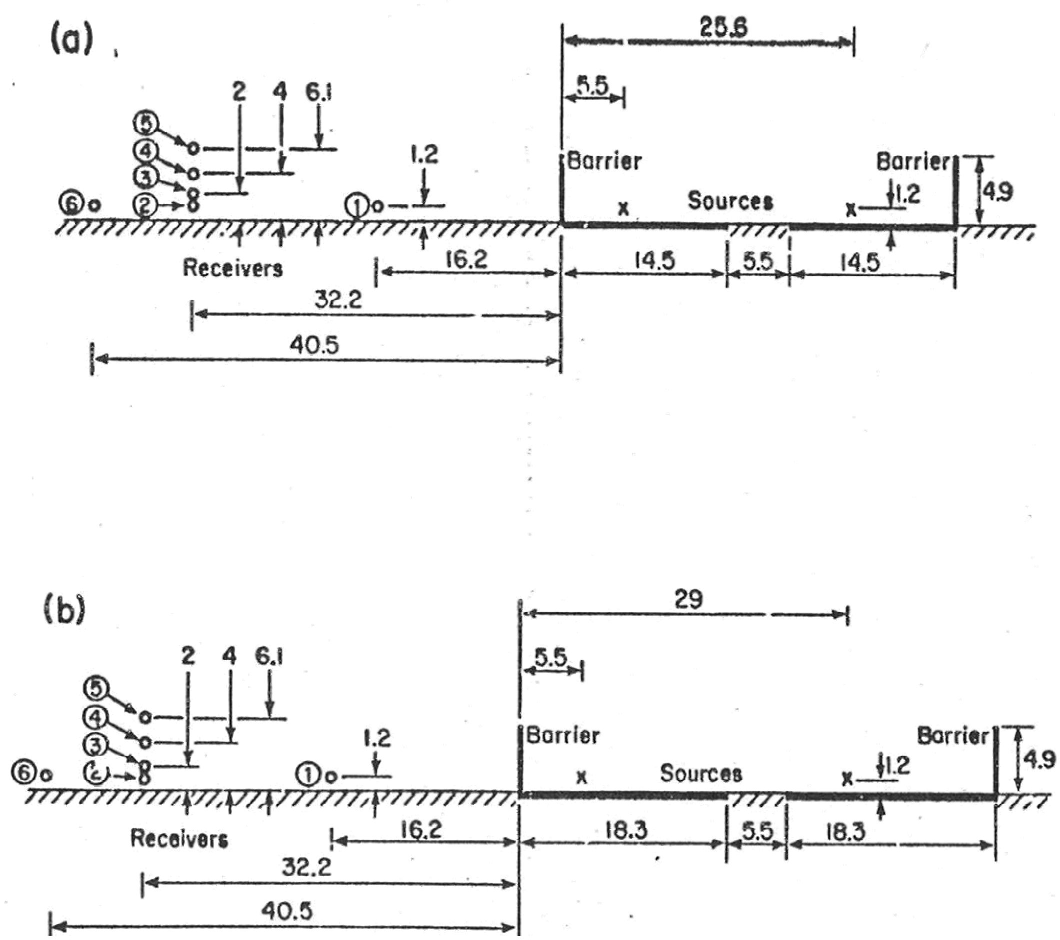


Figure 17: Source-barrier-receiver geometries for the Parallel Barrier experiments. (a) 4-lane highway; (b) 6-lane highway. All dimensions are in meters [May, 1980]

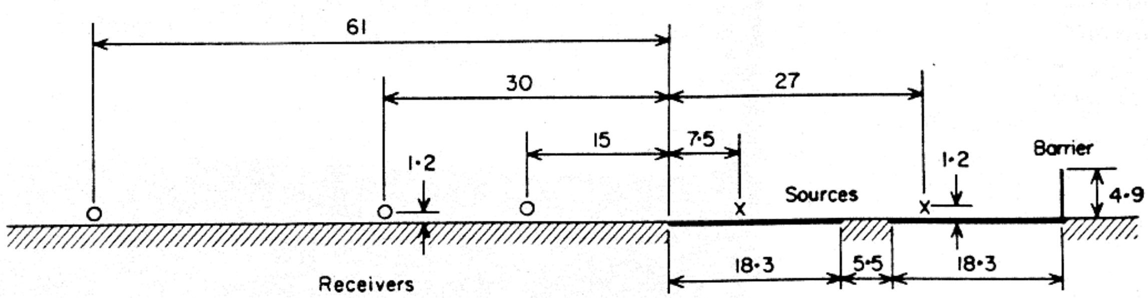


Figure 18: Source-barrier-receiver geometries for the Single Barrier, unprotected receiver experiments All dimensions are in meters [May, 1980]

Watts – Acoustic Performance of Parallel Traffic Noise Barriers

Watts carried out a full scale test in England to identify the nature and size of the effect of sound degradation behind the nearside barrier when parallel reflective traffic noise barriers are placed on both sides of the highway [Watts, 1995]. A noise barrier 30 m (98.4 ft) long was constructed and parallel to this a 7.5 m (24.6 ft) length of barrier was built at a distance of 34 m (111.5 ft). There are post extensions on the barriers and enabled them to be raised to the maximum height to 3 m (9.8 ft). The experiment was done with the microphones located at distances 20 m (65.6 ft), 40 m (131.2 ft), and 80 ft (262.5 ft).

The results are shown in Figure 19 using a bar chart. The author concluded that there was a sound degradation of 4 dB(A) with parallel barriers 2 m (6.6 ft) high placed 34 m apart (width-to-height ratio of 5.2). In the same paper the researchers also found that absorptive barriers and tilted barriers were effective in counteracting the degradation in single barrier performance resulting from unwanted reflected paths.

Watts and Godfrey – Effects on Roadside Noise Levels of Sound Absorptive Materials in Noise Barriers

Watts and Godfrey later carried out the field studies with the primary object to determine, under carefully controlled measurement conditions, the effects on roadside noise levels of applying sound absorptive materials to the traffic face of noise barriers [Watt, 1999]. Two sides were chosen where a modular type of noise barrier had been erected. At one site the road ran in a shallow cut and 3.7 m (12.1 ft) high barriers had been erected on both sides of the road with a separation distance of 34 m (111.5 ft) (Figure 20). At the other site a single 3 m (9.8 ft) had been erected adjacent to an eight lane highway (Figure 17). Highly sound absorptive panels (NRC about 0.9) were mounted on the barriers on the traffic face but reflective on the reverse side. Measurements of traffic noise were made close to the roads both behind and opposite the barriers with the panels in the normal position and then measurements were repeated after the panels had been reversed such that the reflective side faced the traffic. Results for the single barrier and parallel barrier cases are shown in Table 19 and Table 20, respectively. The researchers concluded that there was an increase of noise of generally less than 1 dB(A) and L_{A10} (a statistical descriptor describing the sound level exceeded 10 percent of a measurement period) scales when the barrier face was changed from sound absorptive to reflective at both sites. The researches also noted that the maximum effect in level, L_{A10}, of 2.09±0.44 was recorded at a site and that was expected and consistent with a small number of well controlled field base studies.

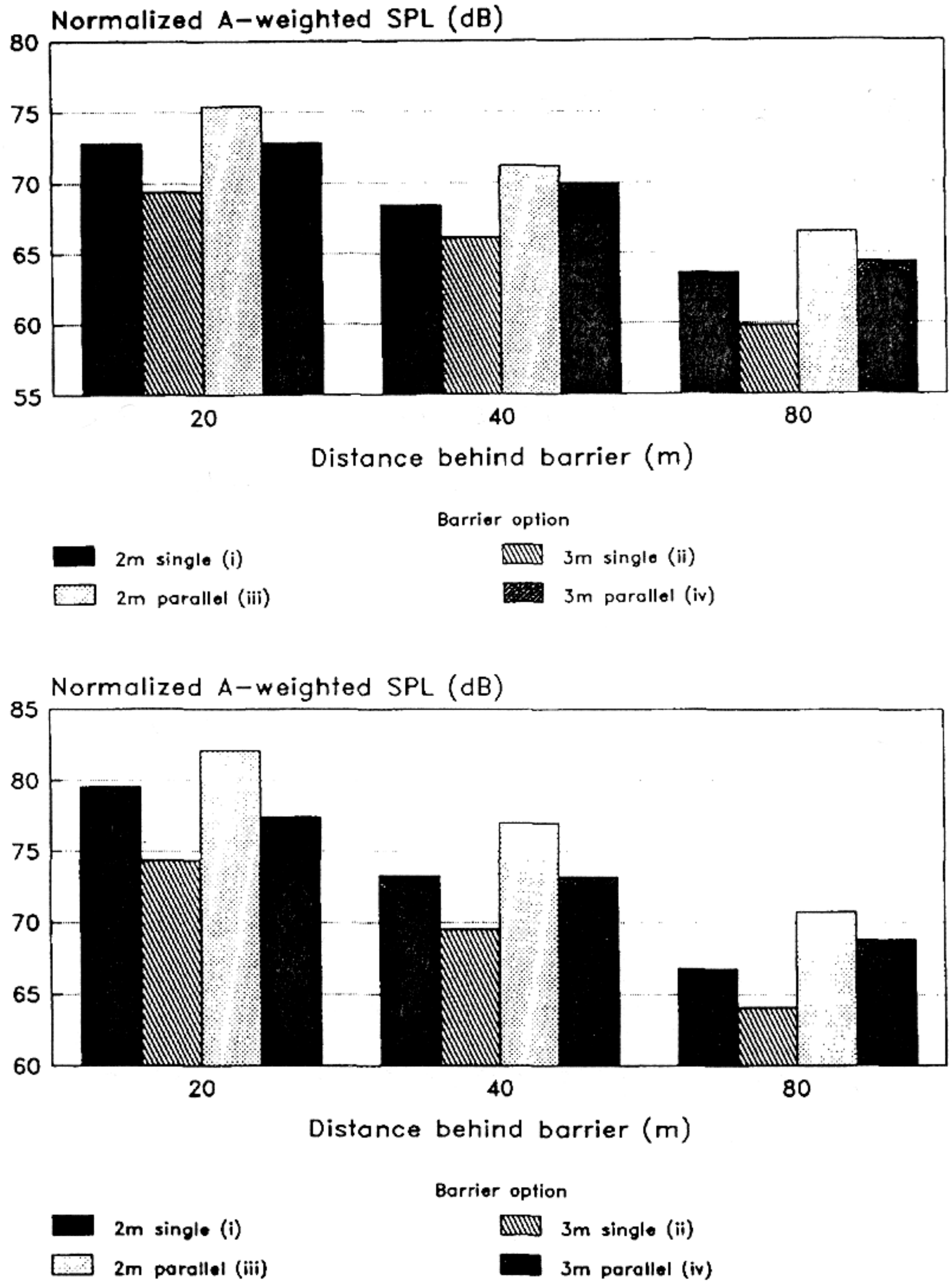


Figure 19: Normalized A-weighted SPL by Distance for Single and Parallel Reflective Barriers

(a) 1.5 m Receiver Height; (b) 4.5 m receiver height [Watts, 1995]

Table 19: Single Barrier Noise Level Differences On the Opposite Side [Watts, 1999]

Receiver Height	Differences in dB(A)		
	Before	After	Change (95% confidence limits)
2.0 m (6.6 ft)	-0.95±0.07	-0.45±0.03	0.50 (±0.15)
5.5 m (18 ft)	1.29±0.11	1.55±0.03	0.26 (±0.23)
9.0 m (29.5 ft)	1.99±0.08	2.15±0.03	0.16 (±0.17)

Table 20: Parallel Barrier Noise Level Differences On the Opposite Side [Watts, 1999]

Receiver Height	Differences in dB(A)		
	Before	After	Change (95% confidence limits)
	15 m (49.2 ft) Behind Barrier		
1.5 m (5 ft)	-19.20±0.28	-18.95±0.49	0.25 (±1.20)
4.5 m (14.8 ft)	-16.00±0.11	-15.13±0.38	0.87 (±0.92)
7.5 m (24.6 ft)	-10.70±0.12	8.42±0.15	2.28 (±0.41)
	30 m (98.5 ft) Behind Barrier		
1.5 m (5 ft)	-20.44±0.41	-20.30±0.30	0.14 (±1.08)
4.5 m (14.8 ft)	-17.71±0.32	-17.75±0.22	-0.04 (±0.82)
7.5 m (24.6 ft)	-15.20±0.26	-14.32±0.18	0.88 (±0.67)

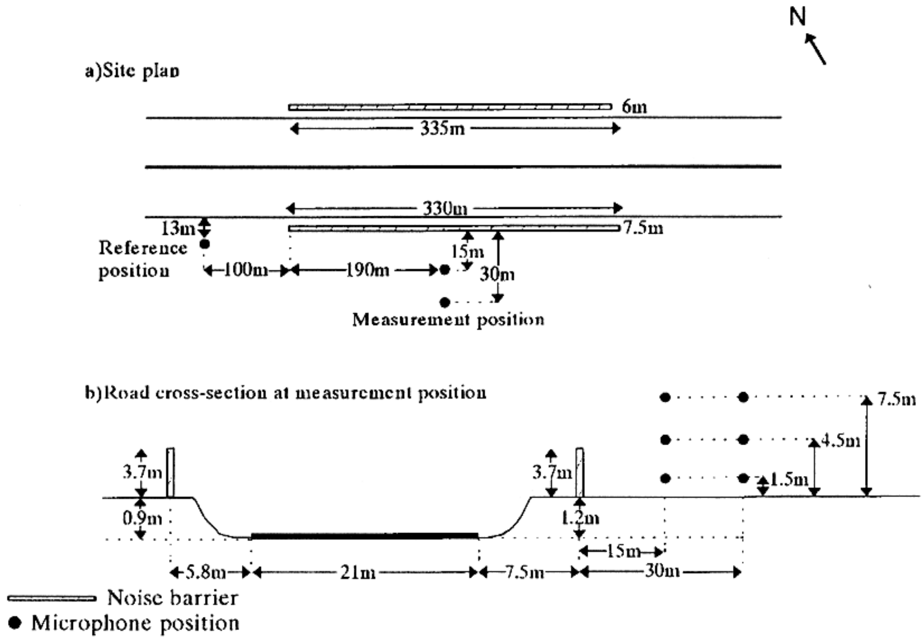


Figure 20: Parallel Barrier Site Details: (a) Site Plan; (b) Road Cross-Section At Measurement Point.

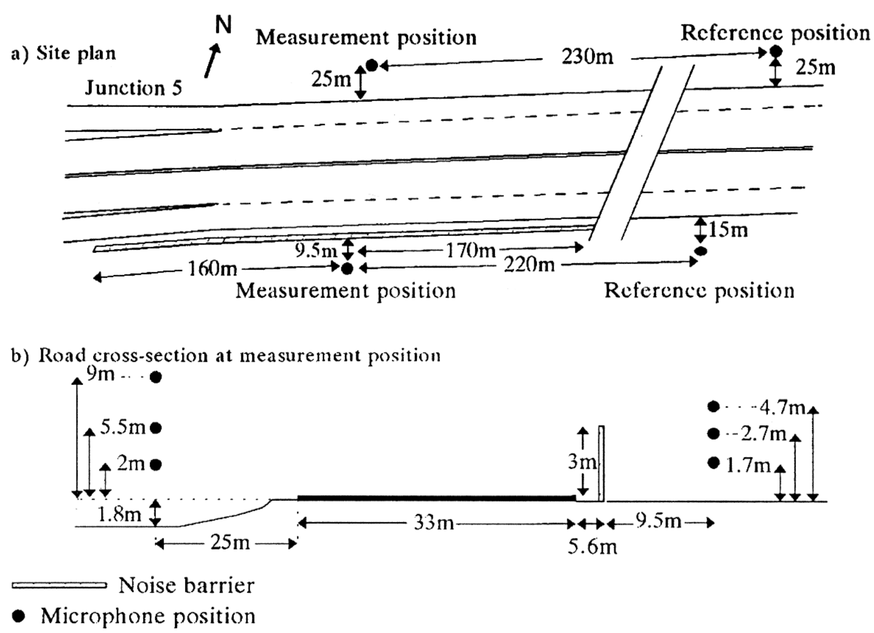


Figure 21: Single Barrier Site Details: (a) Site Plan; (b) Road Cross-Section At Measurement Point.

Maekawa – Multiple Reflections from Parallel Barriers

In 1977, Maekawa published calculations and scale model data on the effect of multiple reflections on parallel noise barrier performance [Maekawa, 1977]. Published scale model data is reproduced in Figure 22. For comparison, Maekawa's single wall attenuation curve is also shown. As may be seen, for reflective wall (top), insertion loss degradations ranged from 0 to 6 dB(A) for receivers unable to see either the source or the far wall (Region II). For receivers able to see the far wall, but not the source (Region I), degradation ranged from 4 to 10 dBA. The lower portion of Figure 22 shows the effectiveness of lining the screens with sound absorbing materials (normal incidence absorption coefficient of 0.48 to 0.93). It shows that the addition of absorptive material almost cancelled out this negative effect. These results were for a 66 ft (20.2 m) wide canyon with wall heights ranging between 16.4 and 49.2 ft (5 to 15 m) representing wall-to-height ratios from 4 to 1.34.

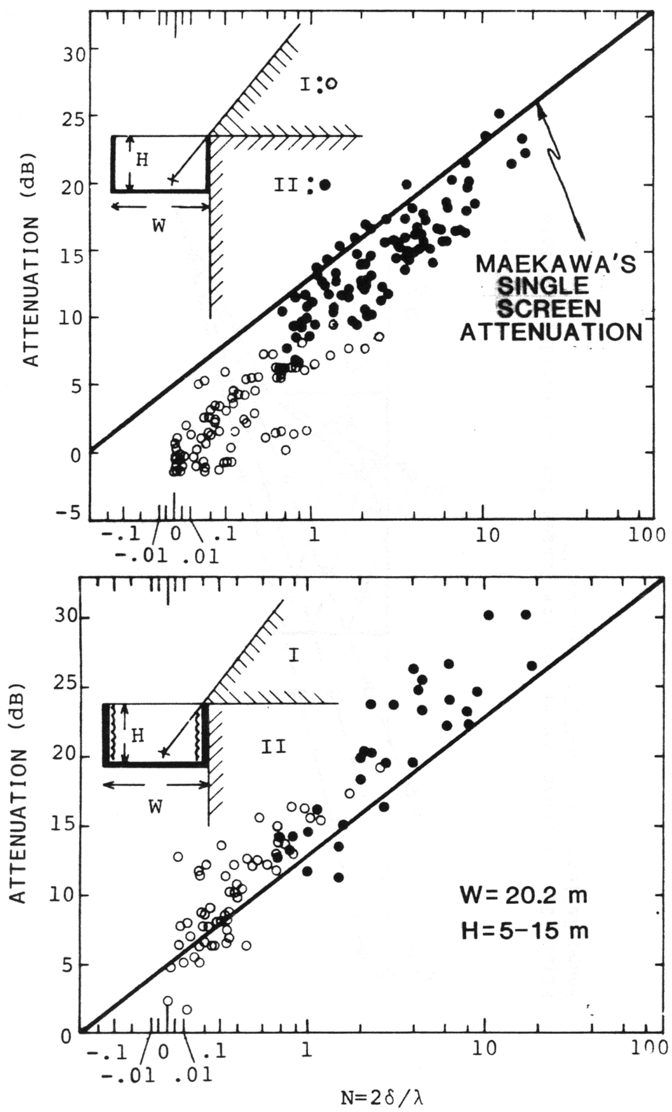


Figure 22: Scale modeled barrier attenuation as a function of fresnel number for reflective (top) and absorptive (bottom) walls. Barriers height (H) ranged from 5 to 15 m and barrier separation (W) was 20.2 m. o – receivers in region 1, above barrier tops; • - receivers in region 2, below barrier tops [Maekawa, 1977]

Hothersall – Scale Modeling of Railway Noise Barriers

Hothersall *et al* carried out experiments in an anechoic chamber using a 1: 20 scale model of a high-speed train to study the insertion loss of various forms of track-side noise barrier [Hothersall, 2000]. The basic forms of the barriers and the configuration of the model are shown in Figure 23 (all dimensions at full scale):

a) A plane vertical screen
b) A plane vertical screen with the top 0.5 m inclined at an angle of 30^{o} towards the track
c) A curved screen of arc radius 3.25 m inclined towards the track with the tangent to the base normal to the round
d) A plane vertical screen fitted with two parallel vertical panels, 0.5 m deep, with a separation of 0.5 m, providing two additional diffracting edges at the same height as the top edge of the main barrier
e) A barrier comprising vertical panels of constant height with a corrugated plane shape

The receivers were positioned 25 m from the near-side track at the heights 0.0 m, 1.5 m, and 4.5 m. The models were studied for both rigid and absorbing grounds. Insertion loss results for the different forms of the noise screens are shown in Table 11. The authors' findings are concluded as below:

1. The insertion loss values for all the screens were lower when the ground behind the barrier was absorbing than when the ground was rigid,
2. The insertion loss for rigid screens was 6-10 dB lower than for similar screens with complete sound-absorbing surfaces.

3. The application of absorbing areas on rigid screens significantly increases the insertion loss by between 3 and 6 dB.
4. The least efficient screen was a corrugated barrier with a rigid surface.
5. The most efficient screens tested were plane and curved barriers with absorbing surfaces and a multiple edge screen with a partly absorbing surface.

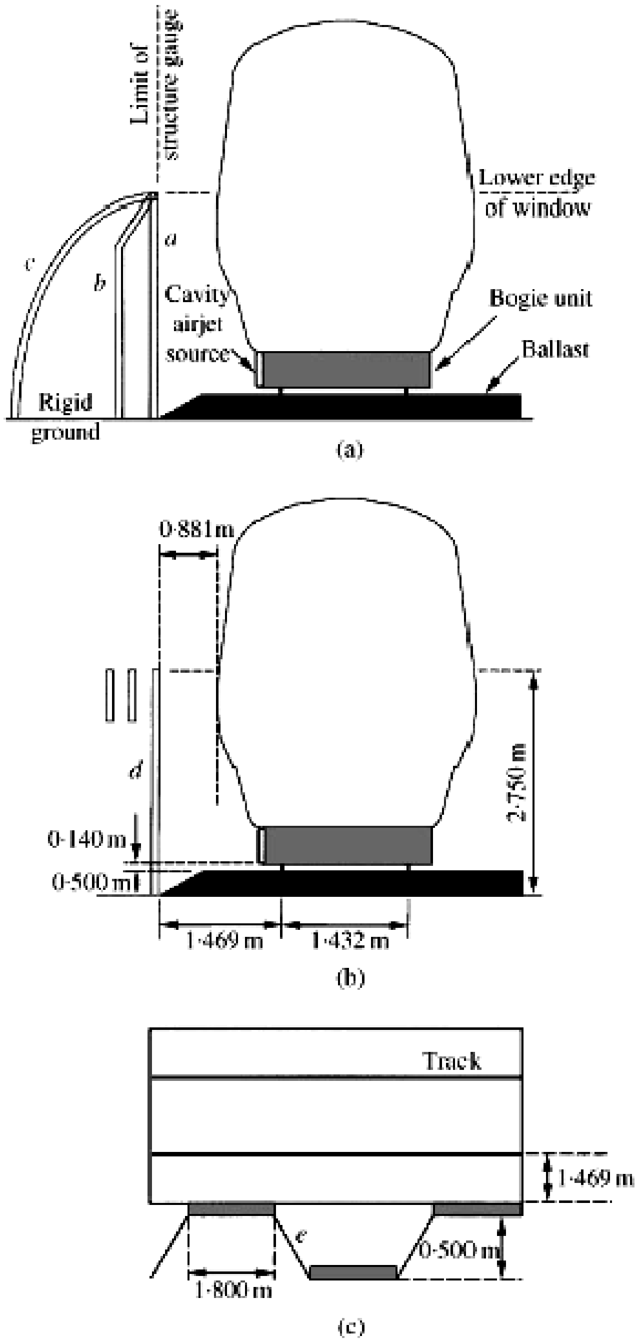


Figure 23: Configuration of the Model. (a) and (b) are cross-sections and (c) is a plan, showing the positions of the barriers described [Hothersall, 2000].

Table 21: Insertion Loss for Different Forms of Noise Screen [Hothersall, 2000].

Barrier type	Insertion Loss					
	Rigid ground			Absorbing ground		
	0.0 m	1.5 m	4.5 m	0.0 m	1.5 m	4.5 m
Free field (SPLs)						
L_{Aeq}	70.6	67.9	68	56.1	62.8	67.9
Plane screen, rigid						
L_{Aeq}	14.8	14.3	13	6.1	10.9	13.8
Plane screen, top 0.8 m absorbing						
L_{Aeq}	20.1	19.2	18.4	10.5	16	19.1
Plane screen, fully absorbing						
L_{Aeq}	24.5	24	23.3	15	20.7	24.3
Multi-edge screen, rigid						
L_{Aeq}	17.8	17.2	14.6	8.4	13.8	15.7
Multi-edge screen, top 0.5 m absorbing						
L_{Aeq}	24.8	23.7	22.8	14.1	20.5	23.7
Cranked screen, rigid						
L_{Aeq}	14.5	14.1	13.4	6.7	11.1	14.5
Cranked screen, top 0.5 m absorbing						
L_{Aeq}	17.9	17.3	16.6	9.7	14.4	17.7
Curved screen, rigid						
L_{Aeq}	18.5	17.1	17.6	10.8	16.5	20
Curved screen, fully absorbing						
L_{Aeq}	22.4	22.5	22.1	14.1	19.7	23.5
Corrugated screen, rigid						
L_{Aeq}	14.2	13.7	12.2	5.7	10.6	13.2
Corrugated screen, part absorbing						
L_{Aeq}	20.2	19.7	18.8	11.9	16.9	20.1

Summary of Literature Review

In this chapter we have reviewed the basic phenomena of sound wave interaction with a partition, single barrier reflections that can affect residents on the opposite side of the road, and multiple reflections of parallel barriers that can cause degradation of the acoustic performance of noise barriers. This work has been reviewed to determine basic theory, the problems caused by sound reflections, and how these reflections may be abated.

This chapter has also reviewed research done in the United States and other countries. Computer models studies, scale modeling and field measurements have been used to determine the degradation of the acoustic performance due to multi reflections within the parallel barriers. Researchers agree that the degradation is caused by reverberant build up within the canyon; however, the magnitude of it has been a subject of considerable controversy. Fleming and Rickey have come out with a rule-of-thumb to determine the degradation by using width-to-barrier height ratio (W/B). This very general rule-of -thumb provides guidance on when degradation may take place and when it reaches a detectable range of nearby residents. But, there is no single and easy to apply equation model to determine the magnitude of the degradation for the receivers behind the near wall. In the next chapter the development of a model using results from some researches in literature is discussed.

Sound absorptive treatment has been found to be an effective way to countermeasure the degradation of acoustic performance on highway barriers due to reflections and also has been reviewed extensively in this chapter. Absorptive treatment systems and the materials for highway use, criteria for selecting materials, and effect of exposure of the absorptive treatment to weather have also been discussed.

Based on this literature review, research has been conducted on the following topics:

1. Selection of 3 tops absorptive treatment material to be used in Florida;
2. Development of an equation model to determine insertion loss model behind parallel barriers; and
3. Determination of the best absorptive placement and required area on highway noise barriers.

Using this information, the most effective treatments for use in Florida can be selected and is discussed in the next chapter.

CHAPTER THREE: METHODOLOGY

This chapter discusses the methodology used in this research. The goals of this methodology are:

1. Present a method that may be used to select the three top absorptive materials for Florida highway noise barriers use;
2. Derive the modeling method to generate a user friendly and easy to use model to determine the magnitude of degradation of acoustical performance due to parallel barriers;
3. Develop a procedure used to test the model using data taken by the UCF Community Noise Lab; and,
4. Determine the best placement location and amount of absorptive materials needed to countermeasure the insertion loss degradation for typical Florida highway noise barriers.

Selection of Three Top Absorptive Treatments

This section discusses the selection of the three top absorptive treatment materials that are most practical for Florida highway noise barriers. Screening criteria to evaluate the performance of materials in five important areas as discussed in the literature review chapter were used to select the materials. These screening criteria, in the order of importance, are:

1. The sound absorbing capacity of materials;
2. Their physical durability;
3. Their acoustical durability;
4. Cleaning and maintenance requirements; and
5. Their flame, fuel, and smoke ratings.

Six commercially available sound absorptive materials for highway noise barriers discussed in the literature review chapter were used for the selection. These materials were selected using ratings 1-4 (4 being excellent, 1 being poor) for all the screening criteria listed above. These ratings are based on product handbook, test data, reference articles and conversation with a consultant on the phone. Descriptions of ratings 1-4 for the screening criteria are shown in Table 22. All these materials (template in Table 23) are rated accordingly and only the three best absorptive materials were selected based on the final rankings.

Table 22: Descriptions of Ratings for Materials Selection

Screening Criteria \ Rating	1	2	3	4
Sound Absorbing Capacity[1]	0-8.0	8.0-8.5	8.5-9.0	9.0-1.0
Physical Durability[2]	Poor	Last for 10 years	Between 10 and 20 years	Last for 20 years or more
Acoustical Durability[3]	Poor	Degrade 20%	Degrade 10%	No Degradation
Cleaning and maintenance requirements[4]	Poor	Often	Some cleaning and maintenance after few years	Minimum or no cleaning and maintenance
Flame, fuel, and smoke ratings[5]	Poor	Fair	Good	Excellent

[1] Based on test data from the materials' literature and handbook
[2] Based on test data, reference articles and conversation with a consultant
[3] Based on test data and reference articles
[4] Based on test data, reference articles and conversation with a consultant
[5] Based on test data from the materials' literature and handbook

Table 23: Template Used for Materials Selection

Materials \ Screening Criteria	Sound Absorbing Capacity	Physical Durability	Acoustical Durability	Cleaning and maintenance requirements	Flame, fuel, and smoke ratings	Total
Glass fiber						
Metal Wool						
Wood fiber planks						
Cementitious materials						
Sound Absorbing Concrete masonry						
Honeycomb material						

Insertion Loss Degradation Model

This part of the methodology discusses the development of the model to more accurately predict insertion loss degradation from barriers. It has been shown from literature that determinations of insertion loss degradation due to parallel barriers have been done through mathematical modeling, scale modeling and field measurements. These studies, nevertheless, require time, money, or complex modeling software to determine the magnitude of degradation. By far, there is still no a simple way, which is user friendly, easy to use and non-computer dependent model to determine magnitude of insertion loss degradation behind parallel barriers. Hence, this research was carried out by using data from previous researches as shown in literature to generate an equation model to determine the insertion loss degradation with only few variables.

In this section, the model is developed in a series of steps as follows:

1. Evaluation and selection of data points from existing literature for the model development
2. Selection of important variables to be modeled and incorporation of these variables into the model equation; and
3. Development and selection of the best model equation by using commercially available graphing software and statistical testing packages.

Evaluation and Selection of Data Points from Literature Review

It has been shown from the literature review chapter that research in insertion loss degradation due to reverberant build-up in parallel barrier has been done through mathematical, scale modeling and field measurement by several researchers. Important researches that are identified during the literature review are summarized as follows:

1. Mathematical modeling:
    a) FHWA Parallel Barrier Nomograph [Simpson, 1976)]
    b) Pejaver and Shadley [Pejaver, 1976]
    c) Bowlby and Cohn [Bowlby, 1986]
2. Scale modeling:
    a) Pejaver and Shadley [Pejaver, 1976]
    b) Maekawa [Maekawa, 1977]
    c) May and Osman [May, 1980]
3. Field measurement:
    a) Fleming and Rickley with the support from Vanderbilt University [Fleming, 1989]
    b) Fleming and Rickley [Fleming, 1992]
    c) Hendriks [Hendriks, 1992]
    d) Watts [Watts, 1995]
    e) Watts and Godfrey [Watts, 1999]

Certain assumptions were made in order to facilitate the modeling process. These assumptions include:

1. Only scale modeling and field measurement researches were chosen to build a database because they were assumed to provide a more representative data to the actual case;
2. Scale modeling and field measurement are assumed to produce the same insertion loss degradation; and
3. The traffic acoustic center is assumed to be in the middle of the roadway during evaluations.

Based on the assumptions above, researches 1a, b, and c were not used because they were done through mathematical modeling. May and Osman's research was also not been chosen because it was done based on the traffic from the near lane source and then far lane source but none was done in the middle of the roadway.

3d was not been chosen because the parallel barrier (as shown in Figure 20) was a combination of barriers and earth berms. 2b is a good article but unfortunately it was not been chosen because the data points were too aggregated and hence was not suitable for use of the model development.

The final selected data for the model development were from sources 2a, 3a, 3b, 3c and 3d. All five research efforts fulfilled the assumptions stated above.

Selection of Important Variables

Important variables to incorporate into the model equation were selected according to their importance and influence to the magnitude of insertion loss degradation.

It was shown that canyon width and barrier height are two very important variables and have to be selected because they were shown to be directly related to the magnitude of insertion loss degradation. It was shown from the literature that smaller the canyon width and barrier height ratios (W/H), higher the insertion loss degradation; conversely, higher the W/H, lower the insertion loss degradation. Canyon width and barrier height ratios (W/H) were also generated and established as a rule of thumb and a guidance to determine the insertion loss degradation [Fleming, 1992], [Hendriks, 1992].

The higher the NRC, the higher the absorption. This means that the energy due to multiple reflections will be reduced and hence less insertion loss will be reduced. So, NRC was chosen as one of the variables.

Research from 1c as shown in Figure 14 shows that automobiles and trucks (and hence, different source height) give different magnitude of the insertion loss degradation, therefore, source height is chosen as one of the variables.

Researches from 1a, 2a, 2b, 3b, 3d, and 3e, show that receivers' height and receivers distance behind the barrier also have great influence on the magnitude of the insertion loss degradation. These results show that the insertion loss degradation is directly proportional to the distant behind the barrier and receiver height. So, receiver height and receiver distant behind barrier were also used to model the equation.

Using these selected variables; details of canyon width, barrier height, NRC, receiver's height, and receiver distance behind barrier were extracted from researches 2a, 3a, 3b, and 3c and summarized in Table 24. These data were used to develop the equation model using commercially available software. The significance of the variables to the model were determined and analyzed through the use of statistic analysis.

Table 24: Data Collected to be Modeled by Using Graphing Software

No.	Source	Δ_{IL}[1] [db(A)]	NRC[2]	SH[3] (ft)	W[4] (ft)	B_H[5] (ft)	R_H[6] (ft)	R_{DB}[7] (ft)
1		3.3	0.00	8	72	15	0	100
2		3.7	0.00	8	72	15	5	100
3		4.7	0.00	8	72	15	10	100
4		5.5	0.00	8	72	15	15	100
5	2a	6.2	0.00	8	72	15	25	100
6		2.5	0.20	8	72	15	0	100
7		3.5	0.20	8	72	15	5	100
8		4	0.20	8	72	15	10	100
9		4.5	0.20	8	72	15	15	100
10		5	0.20	8	72	15	25	100
11		2.16	0.82	8[A]	87	14	6	13
12		3.15	0.82	8[A]	87	14	19	13
13		0.87	0.82	8[A]	87	14	30	13
14		0.26	0.82	8[A]	87	14	6	88
15		2.30	0.82	8[A]	87	14	19	88
16		4.66	0.82	8[A]	87	14	30	88
17		0.58	0.82	8[B]	87	14	6	13
18		3.45	0.82	8[B]	87	14	19	13
19		0.77	0.82	8[B]	87	14	30	13
20	3a	1.54	0.82	8[B]	87	14	6	38
21		3.90	0.82	8[B]	87	14	19	38
22		2.73	0.82	8[B]	87	14	30	38
23		0.81	0.82	8[B]	87	14	6	88
24		1.23	0.82	8[B]	87	14	19	88
25		3.74	0.82	8[B]	87	14	30	88
26		0.38	0.82	2.3[C]	87	14	6	38
27		1.91	0.82	2.3[C]	87	14	19	38
28		0.65	0.82	2.3[C]	87	14	30	38
29		0.00	0.82	2.3[C]	87	14	6	88
30		1.2	0.82	2.3[C]	87	14	19	88
31		4.29	0.82	2.3[C]	87	14	30	88
32		1.5	0.00	5.5	164	18.8	10.8	16
33		2.4	0.00	5.5	164	18.8	21.3	16
34		0.6	0.00	5.5	164	18.8	31.8	16
35		1.9	0.00	5.5	164	18.8	10.8	65.6
36	3b	2.1	0.00	5.5	164	18.8	21.3	65.6
37		2.2	0.00	5.5	164	18.8	31.8	65.6
38		2.4	0.00	5.5	164	18.8	10.8	131
39		2.5	0.00	5.5	164	18.8	21.3	131
40		2.8	0.00	5.5	164	18.8	31.8	131
41	3c	0	0.00	5.5	150	10	0.6	15

42		1.1	0.00	5.5	150	10	10.6	15
43		0.6	0.00	5.5	150	10	18.5	15
44		0.5	0.00	5.5	150	10	1.8	75
45		1.2	0.00	5.5	150	10	11.8	75
46		1.4	0.00	5.5	150	10	19.4	75
47		1	0.00	5.5	150	10	1.8	200
48		1.1	0.00	5.5	150	10	11.8	200
49		1.4	0.00	5.5	150	10	19.4	200
50	3d	2.6	0.00	1.64	112	6.6	5	65.6
51		2.9	0.00	1.64	112	6.6	5	131.2
52		2.9	0.00	1.64	112	6.6	5	262.5
53		2.7	0.00	1.64	112	6.6	15	65.6
54		3.6	0.00	1.64	112	6.6	15	131.2
55		4	0.00	1.64	112	6.6	15	262.5
56		3.3	0.00	1.64	112	9.9	5	65.6
57		3.6	0.00	1.64	112	9.9	5	131.2
58		4.2	0.00	1.64	112	9.9	5	262.5
59		3.2	0.00	1.64	112	9.9	15	65.6
60		3.7	0.00	1.64	112	9.9	15	131.2
61		4.6	0.00	1.64	112	9.9	15	262.5

[1] Δ_{IL} = Measured Degradation
[2] NRC = Noise Reduction Coefficient
[3] SH = Source Height
[4] W = Canyon Width
[B] 8 = Truck B with SH at 8 ft
[5] B_H = Barrier Height
[6] R_H = Receiver Height
[7] R_{DB} = Receiver Distant Behind Barrier
[A] 8 = Truck A with SH at 8 ft
[C] 2.3 = Truck C with SH at 2.3 ft

Development and Selection of the Best Equation Model

A multivariate least squares analysis was chosen to determine the best equation model to determine the insertion loss degradation behind parallel barriers. This analysis was done by using commercially available graphing software. Data from Table 24 were used as variables and used to develop the equation model.

A regression wizard feature from the software was used to allow a curve fit to be produced from the included data. However, there were 6 variables being selected, therefore, none of the parameterized equation in the equation library could be chosen because the maximum variables to be tested in these equations from the equation library were only 2.

Consequently, to be able to test all 6 variables together, a user-defined equation feature was chosen. This feature allows users to use as many variables as possible and edit code to suit the data and the analysis allowing the development of the best curve fit.

Essentially, there were 6 steps done to develop and select the best equation model. These steps are described as follows:

1. Data from Table 24 were inserted into the worksheet of the software with column one as insertion loss degradation (Deg), column two as NRC (NRC), column three as source height (SH), column four as canyon width (CW), column five as barrier height (BH), column six as receiver height (RH) and finally column seven as receiver distant behind barrier (DBB).
2. The models were coded as shown in a and b below and were run separately to test the significance of the variables and to test which of them gave the best fit statistically.
    a. $f = Deg = aNRC + bSH + cCW + dRH + eRH + gDBB$; and
    b. $f = Deg = NRC^a + SH^b + CW^c + RH^d + RH^e + DBB^g$.

    where a, b, c, d, e, and g were exponents determined for the chosen variables.
3. The two models were combined resulting in $f = Deg = aNRC + bSH - CW^c + dRH + RH^e + DBB^g$ to determine the best fit to provide the best overall model;
4. Insignificance variables were excluded from the models listed above according to the statistic analysis output;
5. After the best combination from step 3 was found, natural logarithm was incorporated into the code such as $f = Deg = aNRC - CW^c + d\times\ln(BH) + RH^e + DBB^g$ to check for the overall and individual variable improvement to the model statistically. This was done

from one variable to another, only the one that gave improvement for the overall and individual improvement was applied, otherwise, forms from step 3 was retained.

6. Finally, the best model equation was selected in terms of best R^2 and individual variable and the parameter's t-ratio and p test.

Testing of the Developed Model

A total of 20 sites were measured by the UCF Community Noise Lab as part of FDOT projects to evaluate the barrier effectiveness. Out of these sites, 3 have parallel barriers along the highways. They are:

1. Site A in Jacksonville, FL by Dekalb Street and I-95, visited in January, 1999;
2. Site B in Jacksonville, FL by River Road and I-295, visited in February, 1999; and
3. Site I in Deerfield Beach, FL by NE 1st Terrace, visited in December, 1999;

The testing performed at these sites has as a minimum the microphones locations as shown in Figure 24. Variables such as canyon width, actual and effective barrier height were determined from sites' engineering drawing provided by FDOT and are shown in Table 25 (barrier height is the height above ground at the base of the barrier while effective height is the height above the receiver ground plane). Effective barriers heights and canyon widths of these sites are used as variables for the generated model to determine the insertion loss and the degradation that occurs due to parallel barriers.

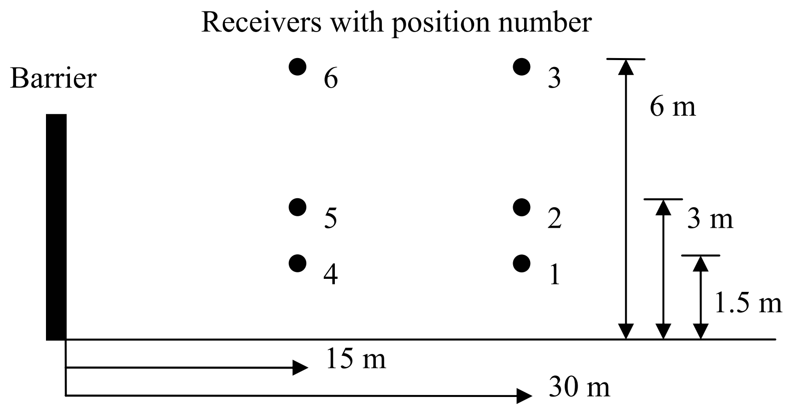


Figure 24: Microphones Location behind the Barrier on the Tested Sites

Table 25: Canyon Width, Actual and Effective Height for the Parallel Barrier Sites

Site	City	Barrier Height (ft)	Effective Barrier Height (ft)	Canyon Width (ft)
A	Jacksonville	18.5	18.5	200
B	Jacksonville	15.6	13.5	283.5
I	Deerfield Beach	13.1	13.1	275

The predicted insertion loss degradations from the generated equation model were compared to predictions from the FHWA TNM reported insertion loss degradations and measured/modeled insertion loss degradation. These comparisons were done through a series of 6 processes as described below:

1. Measured sites data from the sites tested by UCF Community Noise Lab, are reported in two technical reports to FDOT [Wayson, 2002], [Wayson, 2003]. These data were extracted for use in this work.
2. Obtained TNM barrier insertion loss data from sites measured by the UCF Community Noise Lab. This insertion loss data not only included measured data at the sites but also modeled results. TNM data were primarily from single barrier locations. Because these

sites were measured after both walls on the highway have been built, the measured data was assumed to include degradation reducing the overall insertion loss.

3. Insertion loss degradation was derived by using TNM predicted single barrier insertion loss and subtracting the actual measured data to determine the measured/modeled insertion loss degradation. Measured/modeled insertion loss degradation uses the ANSI indirect insertion loss method which uses measured data and adjusted to determine true field insertion loss degradation measured corrected by model.
4. The TNM parallel barrier feature was run to obtain insertion loss degradation – This had not previously been done with the tested sites so this task began by learning and understanding the TNM parallel barrier algorithms to getting the modeled degradation from the input data.
   a) As previously described, TNM parallel barrier feature is an analysis based on ray theory and analyzes the multi reflections on the cross section of a roadway that has parallel barriers. This general feature is illustrated in Figure 25. The insertion loss degradation is calculated by combining all the excess energy contributed by image sources I_1, I_2, and I_2' (of course, more image sources may exist in any general case) and the origin noise source to obtain the sound pressure levels are then subtracted from the diffracted component computed for a single barrier insertion loss.

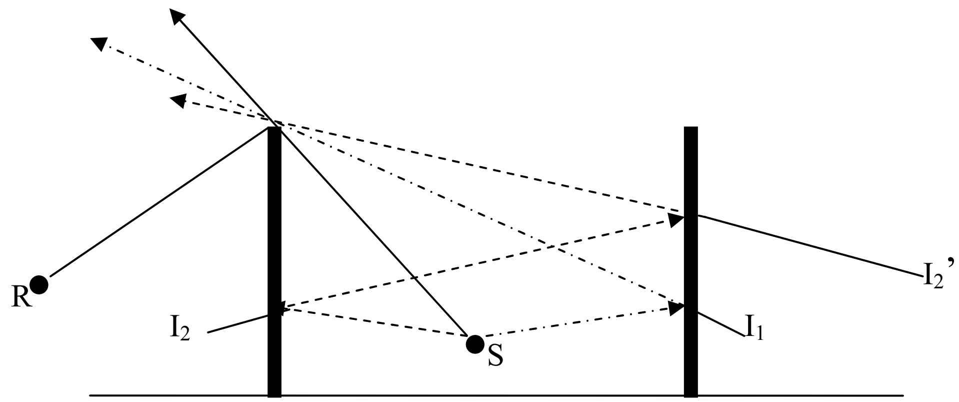


Figure 25: Multiple Sound Reflections for Parallel Barrier showing First Image (I_1, I_2) and Second Image (I_2') Sources.

b) This parallel barrier feature allows users to add a maximum of 25 receivers with different locations behind the barriers. It also allows users to sectionalize the barrier so that analysis of the barrier degradation can be done considering both the application of absorptive treatment on different sections and with different values of the NRC. Suggested work flow when using the parallel barrier analysis procedure is shown in Figure 26.

c) For this part of work, the canyon width and barrier height were modeled according to the values as determined in Table 25. Receivers' locations were modeled according to the actual measured receivers' location that occurred during the actual field measurements as shown in Figure 24.

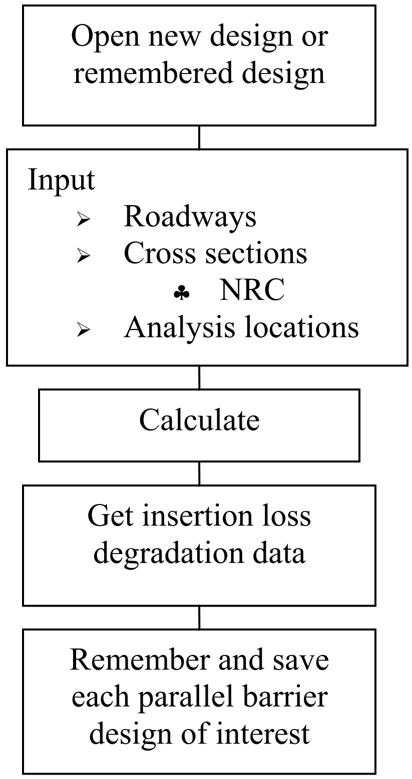


Figure 26: Work Flow for TNM Parallel Barrier Feature

5. Predicted insertion loss degradation was determined using the developed model for this research which was based on the best fit model. The developed model required variables derived from each site to predict the degradation and these variables are shown Table 26

Table 26: Required Variables from Sites to Determine Predicted Insertion Loss using Developed Model.

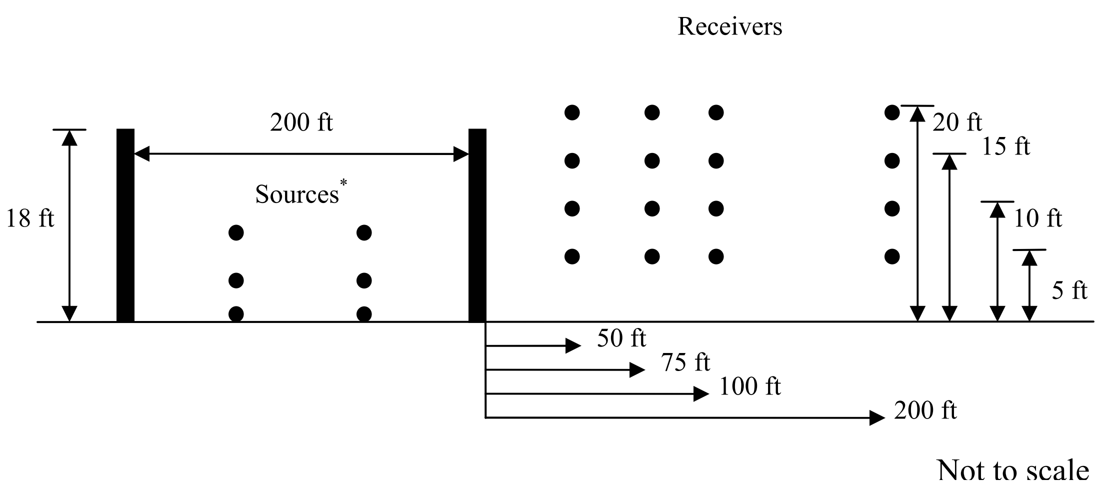
Site	Receiver No.	Canyon Width (ft)	Barrier Height (ft)	Receiver Height (m), (ft)	Receiver Distant Behind Barrier (m), (ft)
A	1	200	18.5	1.5, 4.9	30, 98.4
	2	200	18.5	3, 9.8	30, 98.4
	3	200	18.5	6, 19.7	30, 98.4
	4	200	18.5	1.5, 4.9	15, 49.2
	5	200	18.5	3, 9.8	15, 49.2
	6	200	18.5	6, 19.7	15, 49.2
B	1	283.5	13.5	1.5, 4.9	30, 98.4
	2	283.5	13.5	3, 9.8	30, 98.4
	3	283.5	13.5	6, 19.7	30, 98.4
	4	283.5	13.5	1.5, 4.9	15, 49.2
	5	283.5	13.5	3, 9.8	15, 49.2
	6	283.5	13.5	6, 19.7	15, 49.2
I	1	275	13.1	1.5, 4.9	30, 98.4
	2	275	13.1	3, 9.8	30, 98.4
	3	275	13.1	6, 19.7	30, 98.4
	4	275	13.1	1.5, 4.9	15, 49.2
	5	275	13.1	3, 9.8	15, 49.2
	6	275	13.1	6, 19.7	15, 49.2

6. Insertion loss degradation predicted from the derived model, TNM from a combination of modeled and measured data were then compared to each other.

Determination of Absorptive Treatment Placement and Required Surface Area on a Noise Barrier

This section describes how using the parallel barriers feature in FHWA TNM 2.0 as described in the previous section was used to determine the effect of absorptive treatment. More receivers with wider range of locations were added during this testing.

To begin testing, a barrier typical of those on the Florida's interstate highway system was determined and used for testing. The canyon width and actual traffic data (speed, volume, and type) from Site A were used for the tests; however, barrier height was set to 18 feet so it was easy to sectionalize the barriers into 10 segments (discussed next). With the barrier height assumed to be 18 feet and a canyon width of 200 feet, a width-to-height (W/B) ratio of 11.1 was used. Conventional guidance based on rules of thumb would tend to indicate the barrier degradation would be minimal but this is typical of Florida construction and used first. A total of 12 receivers were modeled behind the barrier to determine the insertion loss degradation of this particular parallel configuration using TNM. These receivers, shown graphically in Figure 27, were located 50, 75, 100, and 200 feet behind the near wall. Elevations used included 5, 10 and 20 feet at each distance from the barrier.



*Source height: 0 ft for cars, 2.33 for medium trucks and 8 ft for heavy trucks

Figure 27: Computation Cross Section for Parallel Barriers

A base case was established by running the model directly, with no absorptive treatment included on the walls (totally reflective with NRC = 0). Degradation values were then determined through TNM output data.

During the analysis, the barrier, being 18 feet in height, was sectionalized into 10 segments of 1.8 feet each. NRCs of 0.80, (lowest NRC for FDOT), 0.85, 0.90 and 0.95 (highest can be used for TNM) were explored for the sectionalized barrier. This allows TNM to model the barrier with partial absorptive treatment at various locations on the barrier which would lead to a substantial cost savings if possible. The changing of the NRC allowed various construction practices; materials needed, and associated costs to be explored.

Alternatives were then tested and compared to the base case. This included changing the location and area of the absorptive treatment (10% increment) as well as the NRC.

The percentage of absorptive treatment requirement and the placement of absorptive explored were extensive and are shown in Figure 28. The tested cases included:

A – Barrier is sectionalized into 10 segments. 10 tests were run with 10% increments of absorptive treatment from the top of the barrier from 10% (partially absorptive) to 100% (fully absorptive);

B – Barrier is sectionalized into 10 segments. 10 tests were run with 10% increments of absorptive treatment from the bottom of the barrier from 10 to 100%;

C – Barrier is sectionalized into 10 segments. 5 tests were run with 20% increment of absorptive treatment from the center of the barrier outwards from 20 to 100%; and, D – Barrier is sectionalized into 10 segments. 5 tests were run with 20% increment of absorptive treatment from the top and bottom (top 10% and bottom 10% each) of the barrier moving inward to finally 100%.

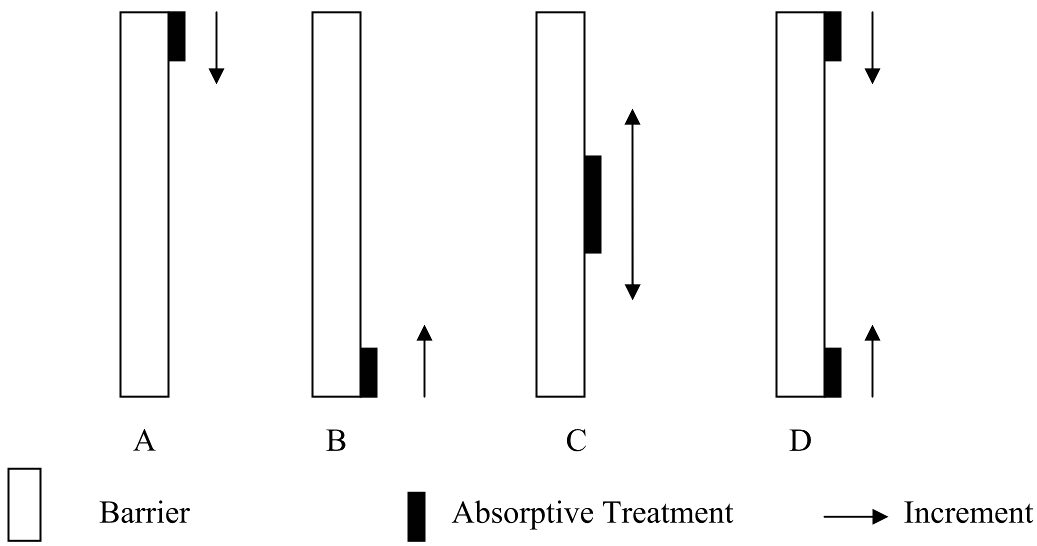


Figure 28. Exploration of Percentage of Absorptive Treatment and Best Absorptive Treatment Placement

Tests of varying sections and combining the amount of absorptive treatment were also carried out. These tests, again, were to further explore various construction practices; materials needed, and associated costs (Cost for low NRC materials range from \$2.50/ ft^2 to \$4.00/ ft^2 while cost for high NRC materials range from \$16.20/ ft^2 to \$29.00/ ft^2 [Witt, 2004]). These tests were only done for the best absorptive treatment placement and required surface on a barrier found from the previous section. Since the best absorptive treatment placement was found to be bottom up pattern with a required surface of 60%, this case was used as a base case for the testing, and is shown in Figure 30. Determination of the best placement and required surface is discussed in next chapter. Seven different modifications were explored as shown in Figure 29 with the same receivers' locations in Figure 27:

A – 50% of absorptive treatment with NRC = 0.80 on the bottom and 50% of absorptive treatment with NRC = 0.4 on the top;

B – 20% of absorptive treatment with NRC = 0.95 on the bottom, 20 % of absorptive treatment with NRC = 0.80 on top of NRC = 0.95 and 60% of absorptive treatment with NRC = 0.4 on the top;

C – 20% of absorptive treatment with NRC = 0.95 on the bottom, 30 % of absorptive treatment with NRC = 0.80 on top of NRC = 0.95 and 50% of absorptive treatment with NRC = 0.4 on the top;

D – Same as C, except 30% NRC = 0.4 on the top;

E – 10% of absorptive treatment with NRC = 0.95 on the bottom, 40 % of absorptive treatment with NRC = 0.80 on top of NRC = 0.95 and 50% of absorptive treatment with NRC = 0.4 on the top;

F – 40% of absorptive treatment with NRC = 0.95 on the bottom and 60% of absorptive treatment with NRC = 0.4 on the top; and

G – Same as F, except 40% NRC = 0.4 on the top.

An NRC of 0.4 was used for the top part of barriers because it is easily obtainable with minimal treatment on the barrier. This design could be obtained with add on cementitous materials or a finned (fluted) wall with minimum increase of barrier construction cost. These materials were tested here to explore efficient costing together with a high NRC absorptive material.

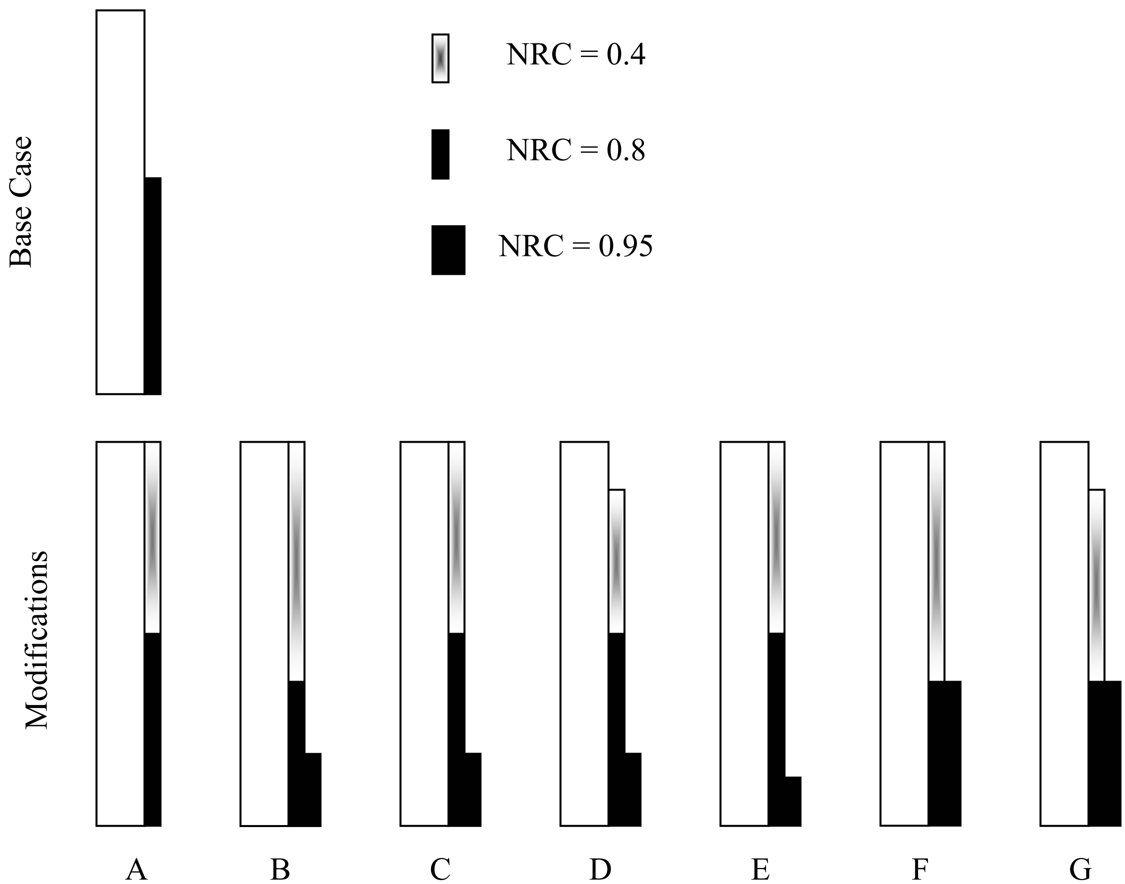


Figure 29: Base Case Absorptive Barrier and Its Modifications

Results from all the works done in this methodology chapter including selection of 3 best absorptive materials, derivation of best model, testing of developed model and placement of absorptive treatment are shown in the next chapter.

CHAPTER FOUR: RESULTS

This chapter shows the results and discusses from the work done based on the methodology discussed in the previous chapter. It is arranged in the following sequences:

1. Selection of three top absorptive materials;
2. Best derived insertion loss model;
3. Testing of developed model; and
4. Effective absorptive treatment placement for a highway barrier.

Selection of the Three Top Absorptive Materials

As shown in Table 27, the three top absorptive treatment materials recommended for Florida highway noise barrier based on performances and ranking schemes are cementitous materials, metal wool and glass fiber. Cementitous material and metal wool would appear to be better than the rest of the materials, both having a good history on the application and both have been used for long periods of time. Metal wool, however, has more cleaning and maintenance requirements because sand and dirt might clog up the voids in the material. Glass fiber, on the other hand, has a history of fiber getting lost and blown away after 10 years of outdoor exposure, and also needs cleaning and maintenance requirements as metal wool does.

However, better quality control should help to avoid these problems. The rest of the materials have not been chosen primarily because of their sound absorbing capacity and physical durability as shown in Table 27.

Table 27: Materials Ranking Using Rating System Based on Screening Criteria

Screening Criteria / Materials	Sound Absorbing Capacity	Physical Durability	Acoustical Durability	Cleaning and maintenance requirements	Flame, fuel, and smoke ratings	Total
Glass fiber	4	2	4	3	4	17
Metal Wool	4	4	4	3	4	19
Wood fiber planks	2	2	4	4	4	16
Cementitious materials	4	4	4	4	4	20
Sound Absorbing Concrete masonry	2	3	4	3	4	16
Honeycomb material	2	3	4	3	4	16

Results from the Developed Model

The best equation model found is shown in Equation 9. Table 28 shows that the t ratios and p values of all five selected variables are statistically significant. These estimated parameters shown in Table 28 were used in the development of Equation 9. The best fit model found was used to determine insertion loss degradation behind the parallel barrier due to reverberant build-up within the canyon.

Variable source height (SH) was found to be not statistically significance to the model and therefore was removed.   Perhaps wider range of source height and more data points are needed in order to truly verify the dependency of it to the developed equation model.

Table 28 Statistical Analysis for the Parameters of the Best Equation Model

Parameter	Estimate, β	Std. Error	t ratio	p value
a	-2.17	0.4697	-4.6128	<0.0001
b	0.42	0.0224	18.6551	<0.0001
c	1.97	0.3444	5.7117	<0.0001
d	0.29	0.0540	5.4118	<0.0001
e	0.27	0.0242	11.0041	<0.0001

$$Deg = -2.17NRC - CW^{0.42} + 1.97\times\ln(BH) + RH^{0.29} + DBB^{0.27} \quad (9)$$

where Deg = insertion loss degradation, dB(A)
NRC = noise reduction coefficient
CW = canyon width, ft
BH = barrier height, ft
RH = receivers' height, ft
DBB = receivers' distant behind barrier, ft

Figure 30 displays a plot of the predicted degradation using Equation 9 versus the measured/modeled degradation as described in the last chapter. It is shown that the correlation coefficient is moderately high with an R^2 value of 0.55.

Additional work was done to visualize the effect of canyon width and the insertion degradation by using the best equation model found. This was done by inserting different receiver locations into the equation model with the assumed barrier height of 18 feet and different canyon width as shown in the Figure 31.

It is shown in Figure 30 that canyon width of 170 feet is required in order to prevent insertion loss degradation which is perceivable by human ears. Interestingly, according to Figure 31 and guidance from the rule of thumb by FHWA; the results match very well. When W/B ≥

10:1, degradation higher ≥ 3 dB(A); when 10:1≤ W/B ≤ 20:1, 0 ≤ degradation ≤ 3 dB(A). This was very promising and tending to validate the applicability of the developed model.

Since this developed model is generated with a limited range of data from the literature, there may well be limitations to its applicability over a wide range of test conditions. Also, a negative degradation is sometimes given when the canyon width gets too wide, leading to limits on the widths that can be used. This does not mean that absorption of sound is reducing the overall levels but it does mean that the degradation is insignificant and might not even be measurable. Therefore, whenever negative insertion loss degradation is encountered while using the equation model, it should be assumed that the insertion loss degradation is zero.

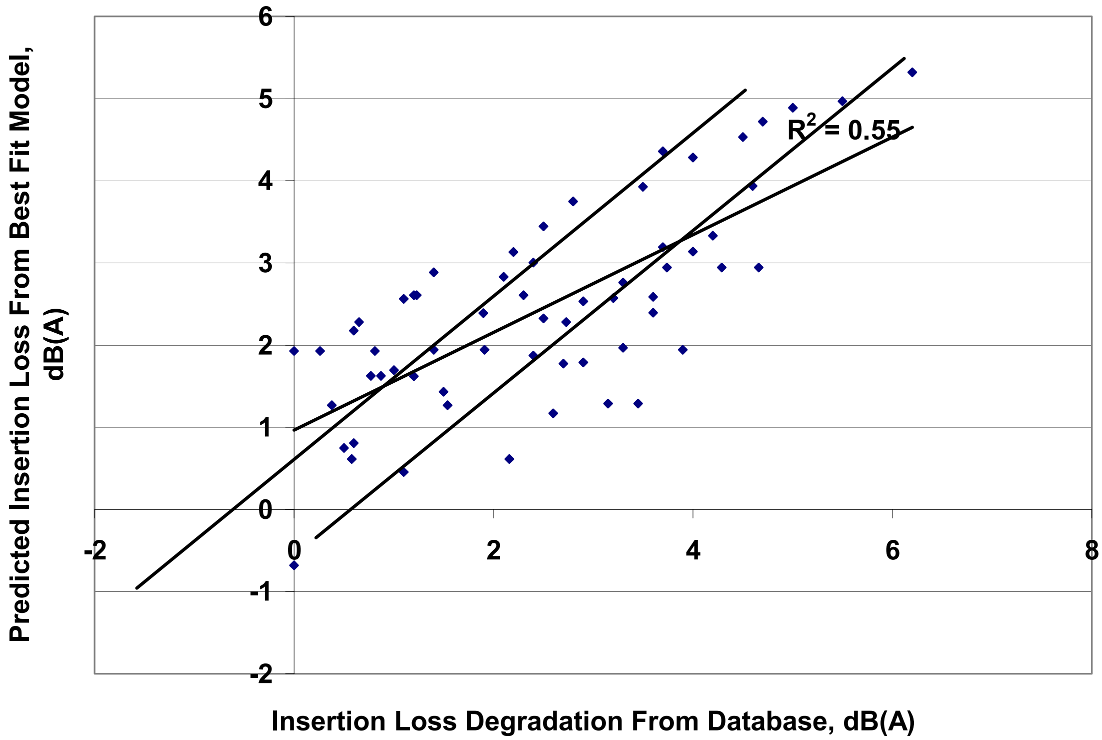


Figure 30: Measured Insertion Loss Degradation from Literature versus Predicted Insertion Loss Degradation from the Generated Equation Model

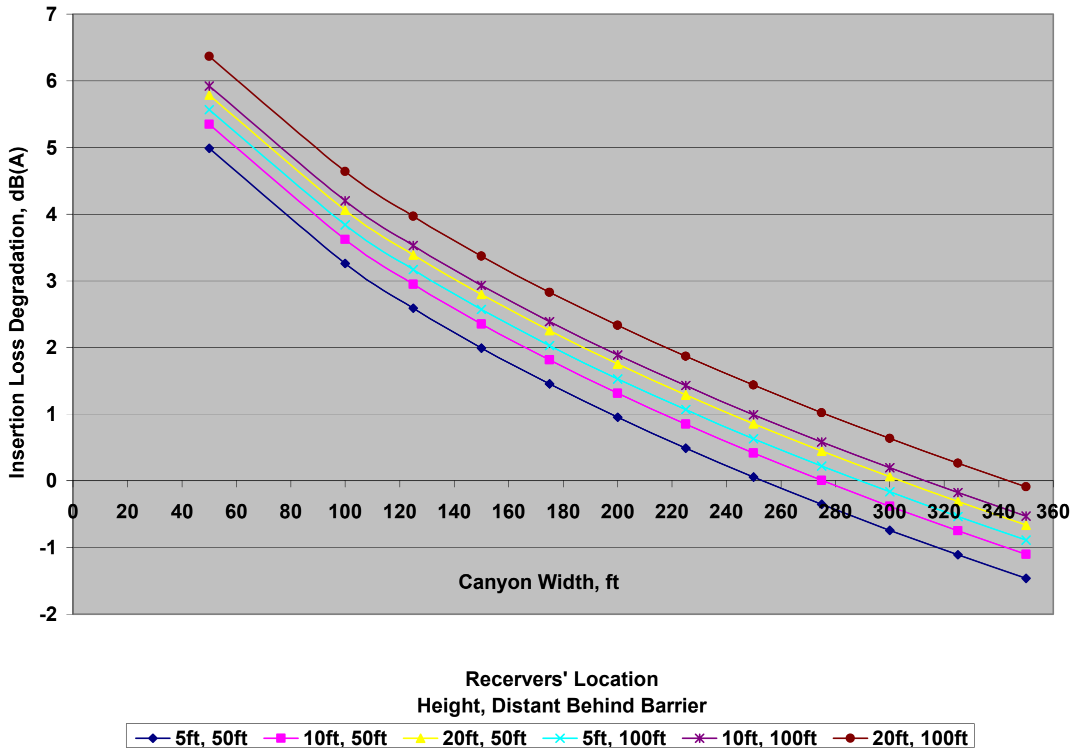


Figure 31: Insertion Loss Degradation versus Canyon Width for Different Receivers' Location with Barrier Height of 18 feet

Testing of the Derived Model

Table 29 shows the results of insertion loss degradations from three computations: measured/modeled, predictions from TNM, and predictions from the best equation model. In order to have a better visualization of these results for the comparisons, they were plotted in bar charts as shown in Figure 33 to Figure 34.

Table 29: Comparison of True Degradation, Predicted Degradation from TNM and Predicted Degradation from Model Equation

Site	Ivie Number	1	2	3	4	5	6
A	Actual Measured Data, dB(A)	62.9	63.4	67.9	-	65.3	68.6
	TNM Single Barrier Data, dB(A)	61.7	62.7	64.9	-	62.9	66.9
	True Degradation, dB(A)	1.2	0.7	3.0	-	2.4	1.7
	Predicted Degradation from TNM, dB(A)	3.3	4.1	5.5	-	3.2	4.6
	Predicted Degradation from model equation, dB(A)	1.6	1.9	2.4	-	1.4	1.8
B	Actual Measured Data, dB(A)	63.7	66.1	67.7	64.5	66.5	69.8
	TNM Single Barrier Data, dB(A)	63.0	64.9	70.4	63.5	65.9	74.7
	True Degradation, dB(A)	0.7	1.2	-2.7	1.0	0.6	-4.9
	Predicted Degradation from TNM, dB(A)	1.7	2.2	0.4	2.1	2.6	1.8
	Predicted Degradation from model equation, dB(A)	-0.5	-0.1	0.3	-1.0	-0.7	-0.2
I	Actual Measured Data, dB(A)	63.1	65.2	69.2	65.0	66.4	72.1
	TNM Single Barrier Data, dB(A)	66.1	68.4	72.7	65.9	68.2	77.0
	True Degradation, dB(A)	-3.0	-3.2	-3.5	-0.9	-1.8	-4.9
	Predicted Degradation from TNM, dB(A)	1.8	2.3	0.2	2.1	2.6	1.7
	Predicted Degradation from model equation, dB(A)	-0.4	0.0	0.4	-1.0	-0.6	-0.2

It is clearly shown in Figure 32 that insertion loss degradation exists at Site A. This site has a W/B ratio of 10.8:1, which is very close to the guidance and rule of thumb of 10:1 that can have degradation loss of 3 dB(A) or smaller. Site A shows the highest measured/modeled insertion loss of 3 dB(A) when the receiver's location is at 30 m (98.2 ft) behind the wall and at a height of 6 m (19.7 ft), as well as the highest values from TNM and model prediction. If compared to measured/modeled insertion loss degradation, TNM seems to over predict the degradation; in contrast, the generated equation model seems to give better prediction results.

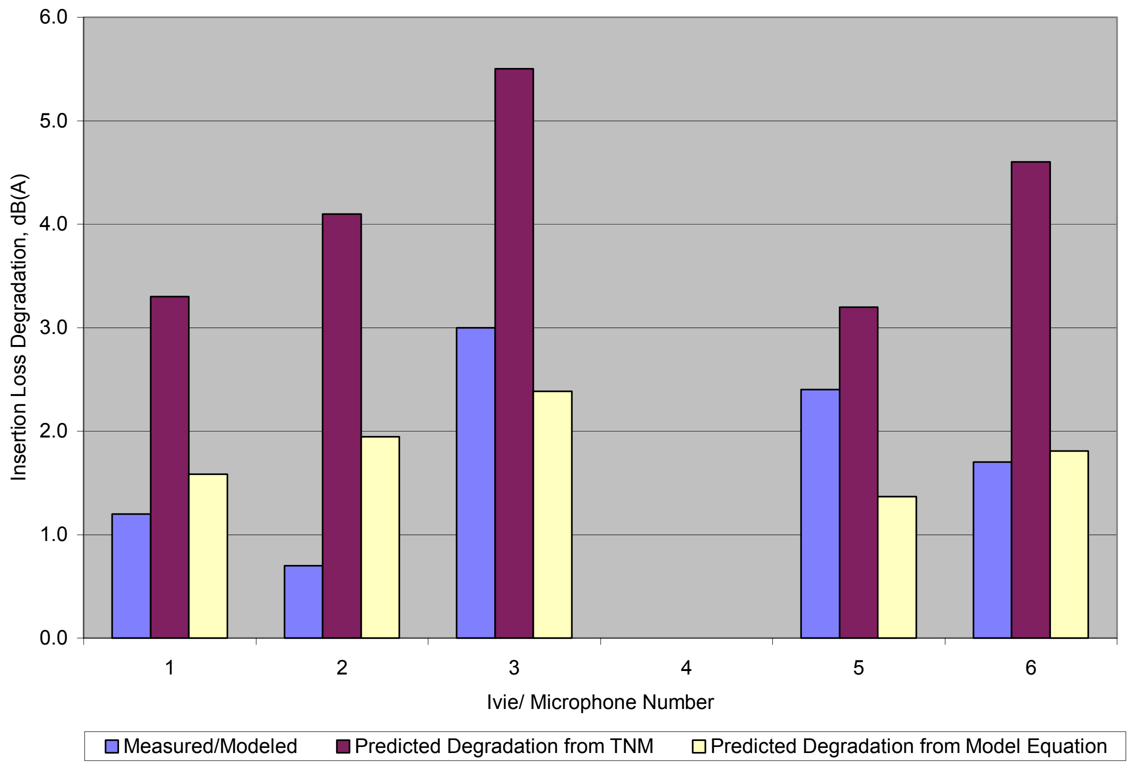


Figure 32: Comparison of Insertion Loss Degradation from Measured/Modeled* and Both Predicted from TNM and Model Equation for Site A

* Combination of Measured data and Modeled results from TNM as described in Methodology Chapter (Testing of Developed Model

Site B has a W/B ratio of 21:1 which by the rule of thumb, is in the category of no measurable insertion loss degradation. The measured/modeled insertion loss degradation, however, shows that this site does have a measurable degradation of 1.2 dB(A). While this is below human perception, there would appear to be some degradation even with this very wide W/B ratio. Negative insertion loss degradations were predicted for both measured/modeled and developed model results. The negative measured/modeled insertion loss degradation could mean that there is an inaccuracy of predictions but exactly where is debatable. This inaccuracy led to higher unaffected, predicted insertion losses and thus resulted in negative predicted degradation. As such, the developed model predicted that there is no measurable degradation occurring at this site. TNM, on the other hand, appears to over predict the degradation if compared to the measured/modeled results; in contrast, the generated equation model seems to give better prediction results.

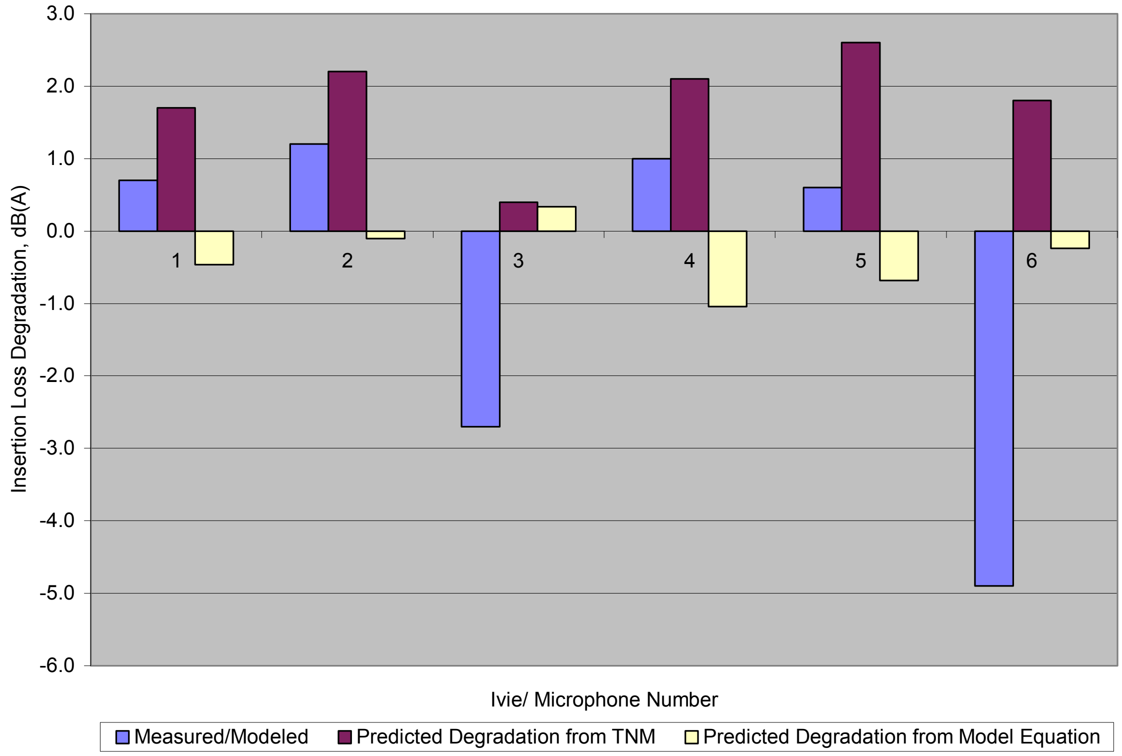


Figure 33: Comparison of Insertion Loss Degradation from Measured/Modeled and Both Predicted from TNM and Model Equation for Site B

Site I also has a W/B ratio of 21:1 which is in the category of no measurable insertion loss degradation from the rule of thumb guidance. No positive measured/modeled insertion loss degradation was predicted at this site and in fact, results were negative. This again could due to the inaccuracy of the TNM predictions or there was not any measurable insertion loss degradation most likely because the W/B ratio is too large. As can be seen from the Figure 34, TNM predicted as high as 2.6 dB(A) of insertion loss degradation for one of the receivers. The developed model predictions of negative degradation imply that negative values most likely should be interpreted as no measurable. Again, it can be seen that TNM over predicts insertion loss degradation if compared to measured/modeled results and in contrast, the generated equation model seems to give better prediction results.

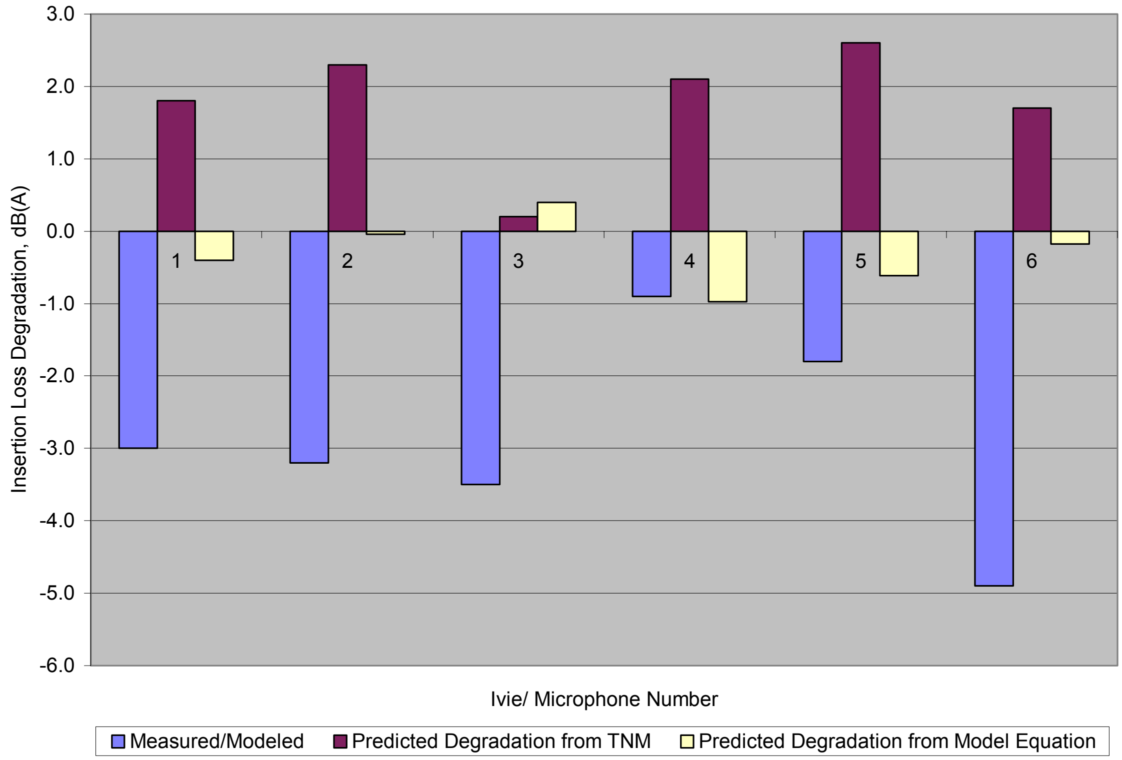


Figure 34: Comparison of Insertion Loss Degradation from Measured/Modeled and Both Predicted from TNM and Model Equation for Site I

Absorptive Treatment Materials Placement and Area Required

Absorptive Treatment Materials Placement

Figure 35 to 55 illustrate the insertion loss degradation behind parallel barrier when applying different patterns of absorptive treatment on the barrier. The reader is reminded that this was done by use of the TNM Parallel Barrier Module and testing was done as described in the previous chapter using defined percentages of area in different locations as shown in Figure 28. These results show that the application of absorptive treatment with the pattern covers from bottom up (Figure 28 B) has the highest efficiency in terms of degradation improvement regardless of the NRC used. Following the bottom up pattern in terms of degradation improvement in descending order are spreading outward from middle pattern (Figure 28 C), spreading inward from top and bottom pattern (Figure 28 D) and top down pattern (Figure 28 A).

Coverage from the middle spreading shows better improvement of degradation on few receivers than bottom up pattern but overall, as can be seen from Figure 35 to 55, the bottom up pattern would appear to be the best choice based on the state-of-the-art, cross-section modeling.

Test results for these four tested patterns regardless of the NRC applied on the absorptive treatment (see Figure 35 to 55) also prove that the absorptive treatment must be placed on the bottom and middle section of the barriers in order to get the best results in degradation improvement. This is probably due to the sound wave coming from the tire on the road, the angle that this makes between the wall and receiver, and this crucial path being absorbed by the absorptive material before they have any chance to reverberate within the canyon and cause insertion loss degradation behind the parallel barrier.

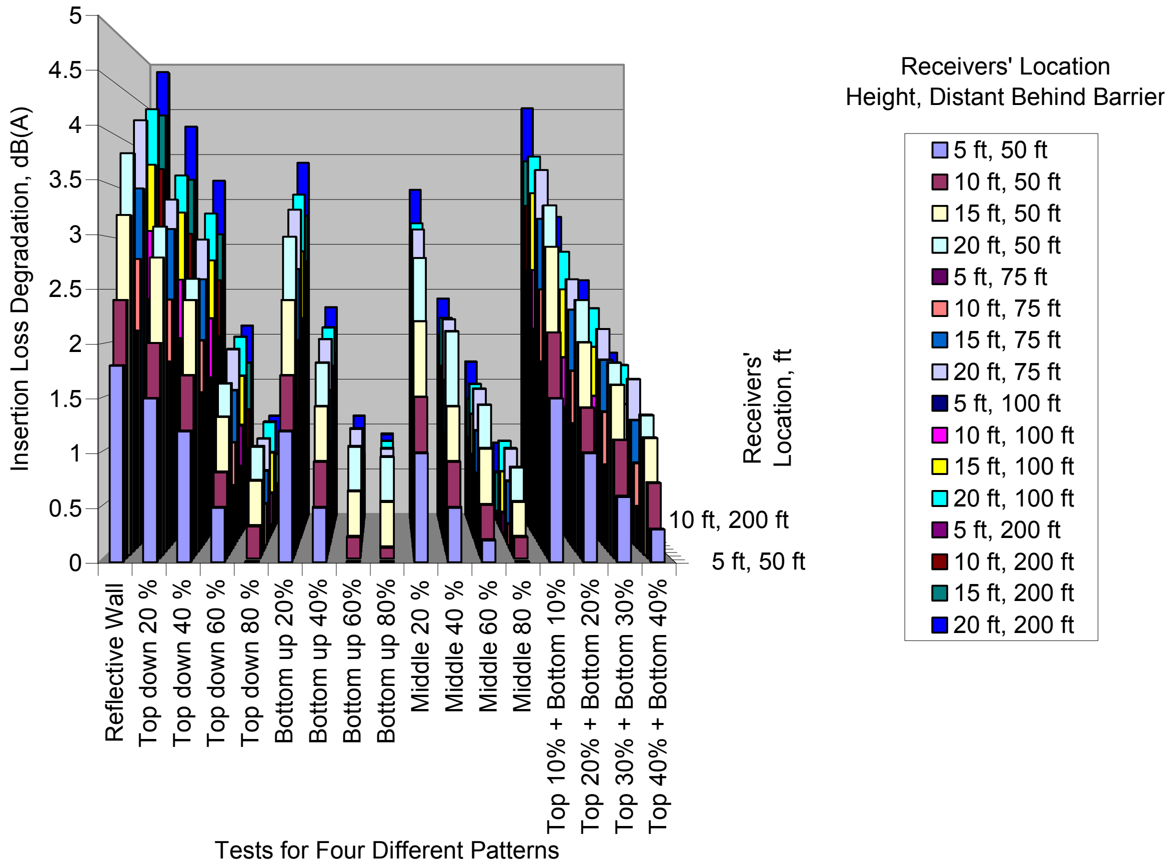


Figure 35: Determination of Best Absorptive Treatment Place with Four Different Patterns using NRC of 0.8

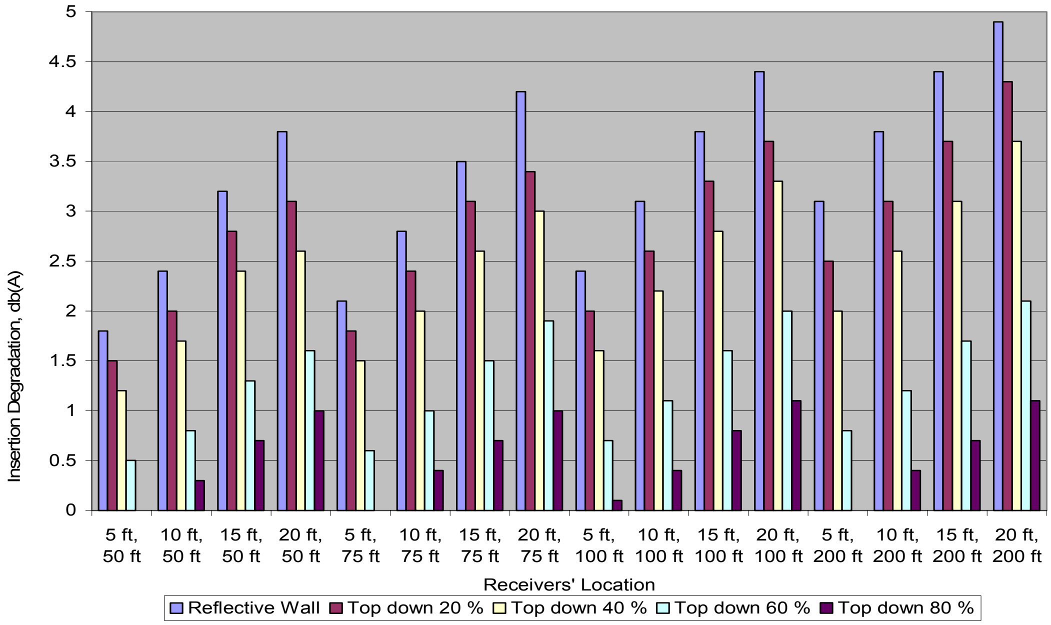


Figure 36: Determination of Best Absorptive Treatment Place with Top Down Pattern using NRC of 0.8

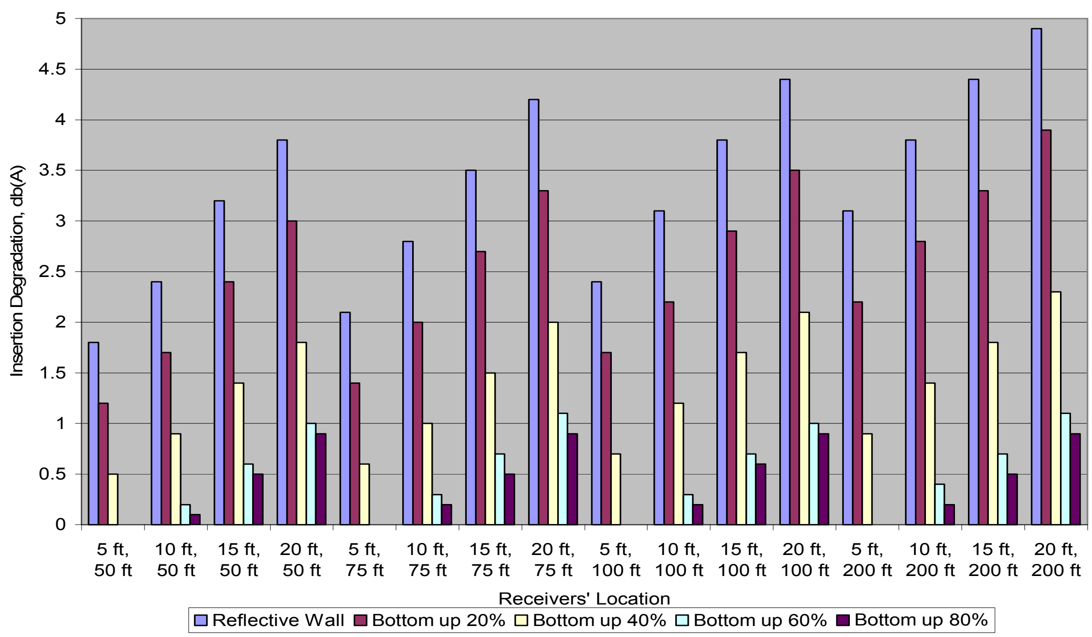


Figure 37: Determination of Best Absorptive Treatment Place with Bottom Up Patterns using NRC of 0.8

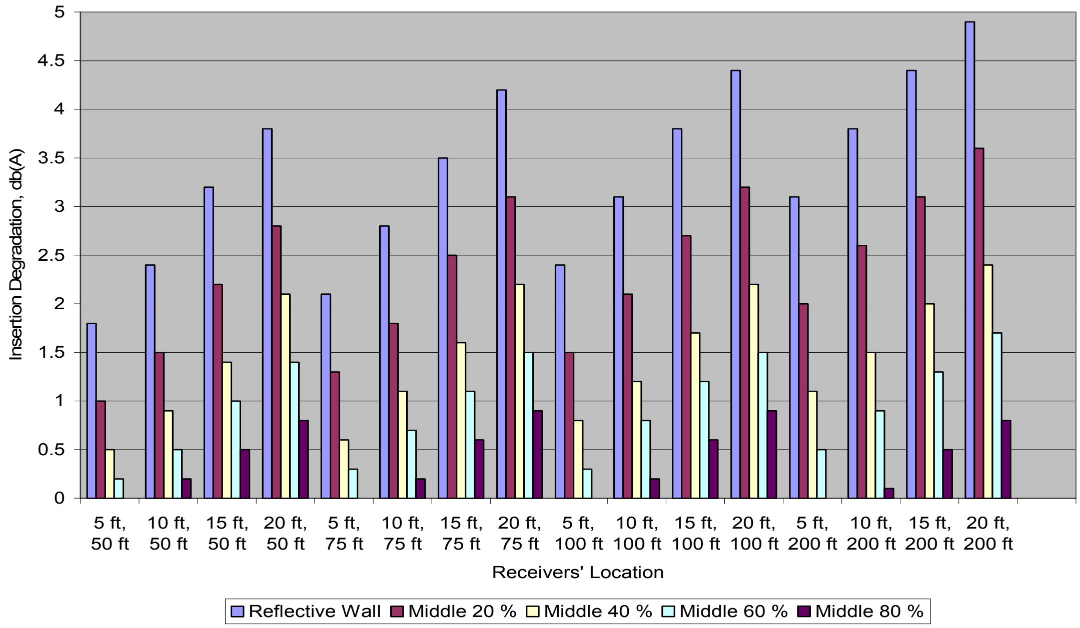


Figure 38: Determination of Best Absorptive Treatment Place with Middle Spreading Outward Pattern using NRC of 0.8

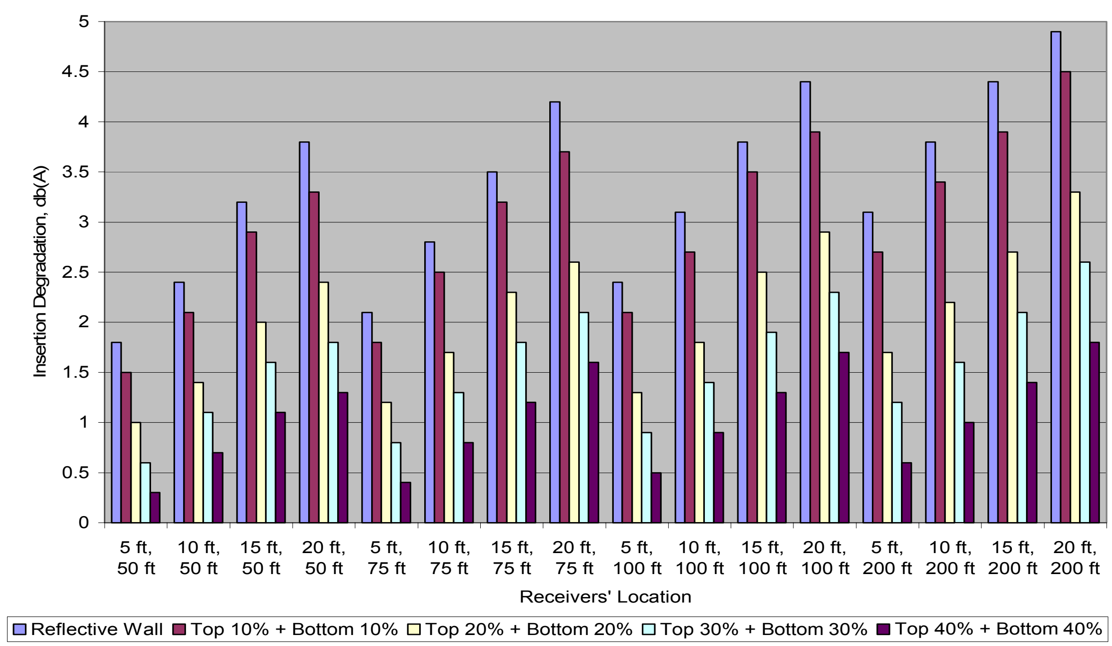


Figure 39: Determination of Best Absorptive Treatment Place with Top and Bottom Spreading Inward Pattern using NRC of 0.8

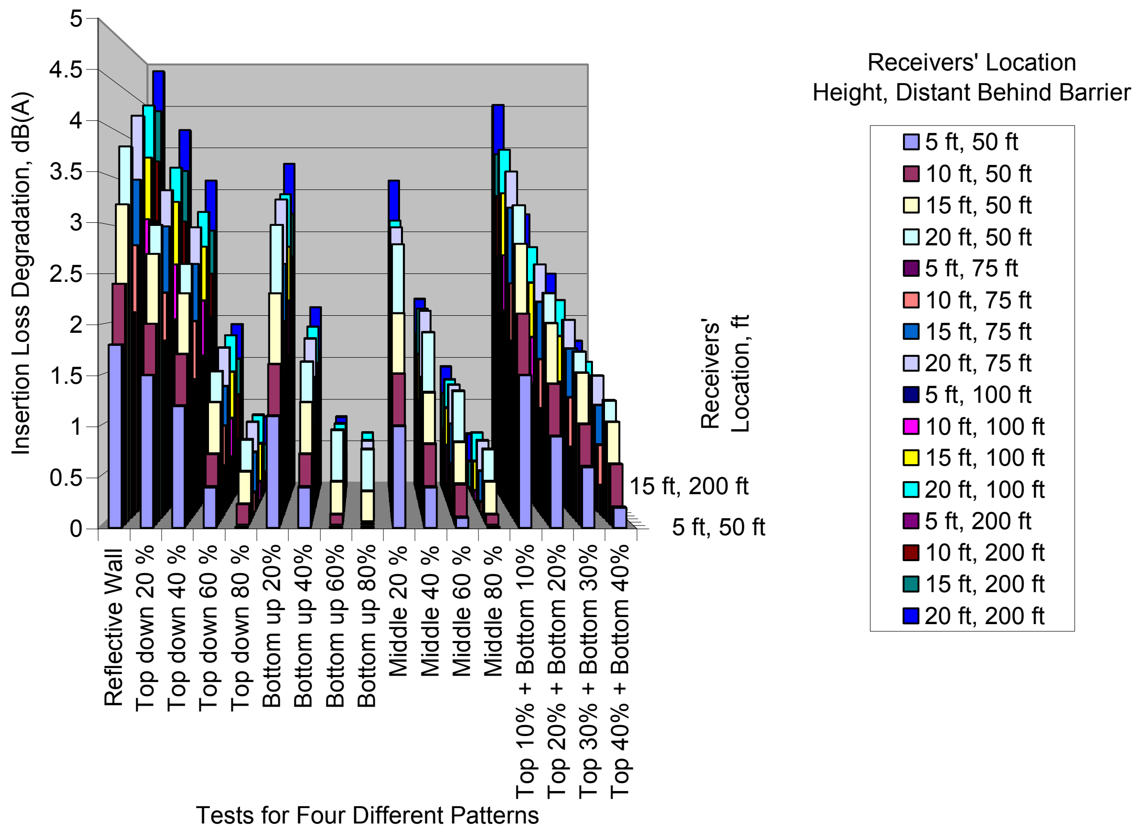


Figure 40: Determination of Best Absorptive Treatment Place with Four Different Patterns using NRC of 0.85

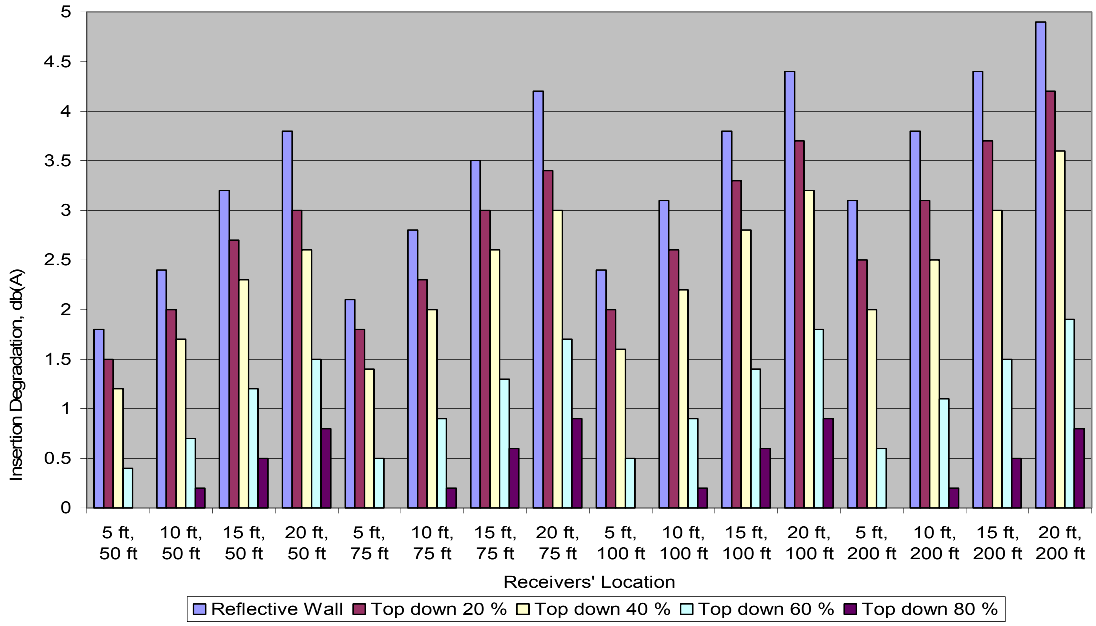


Figure 41: Determination of Best Absorptive Treatment Place with Top Down Pattern using NRC of 0.85

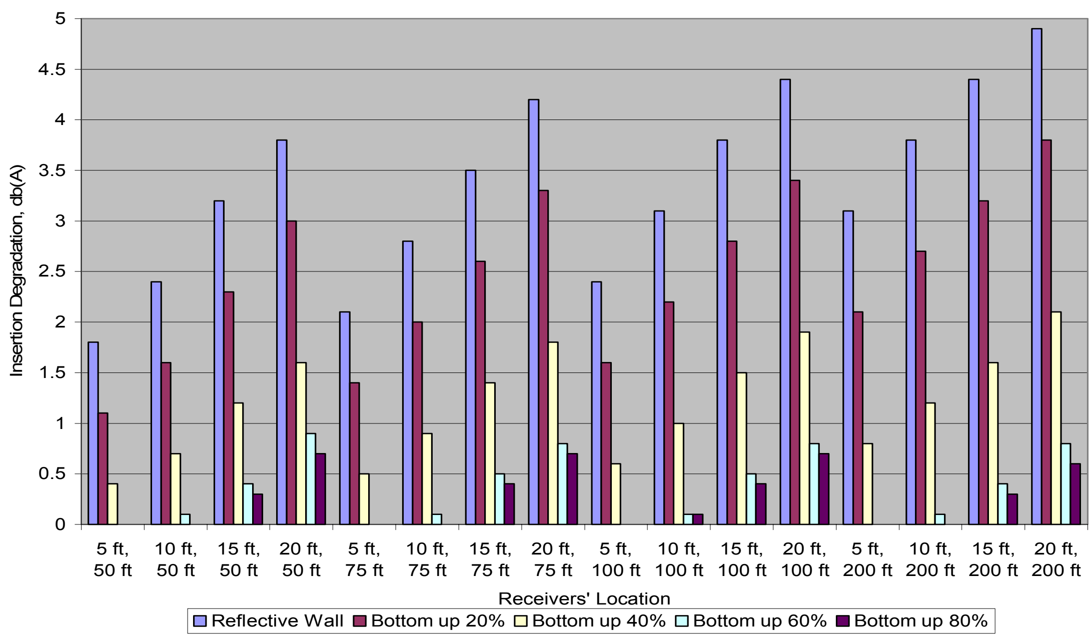


Figure 42: Determination of Best Absorptive Treatment Place with Bottom Up Pattern using NRC of 0.85

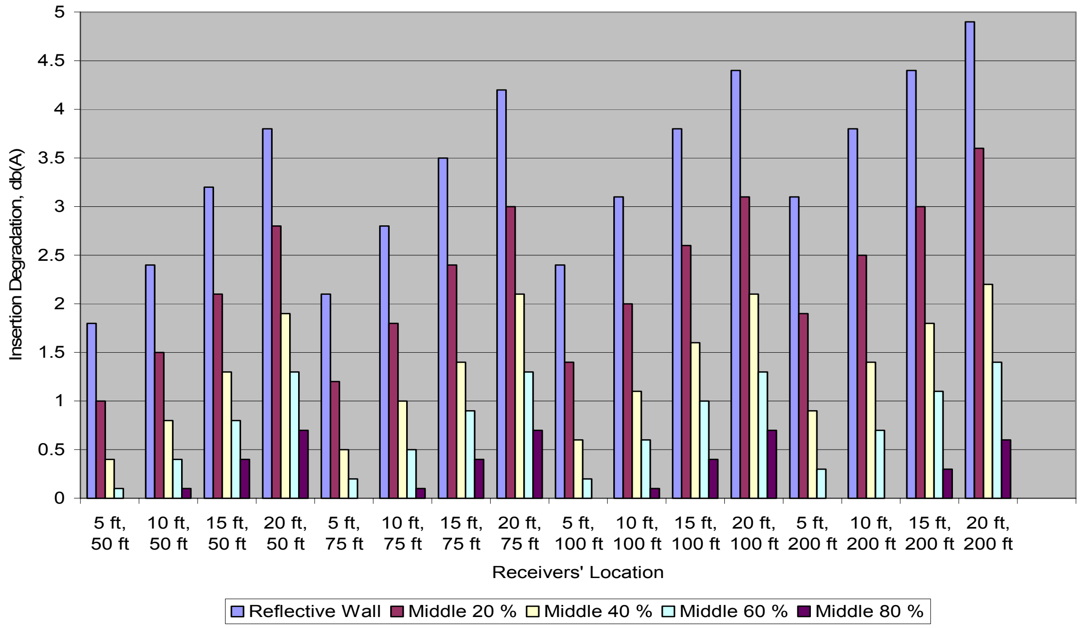


Figure 43: Determination of Best Absorptive Treatment Place with Middle Spreading Outward Pattern using NRC of 0.85

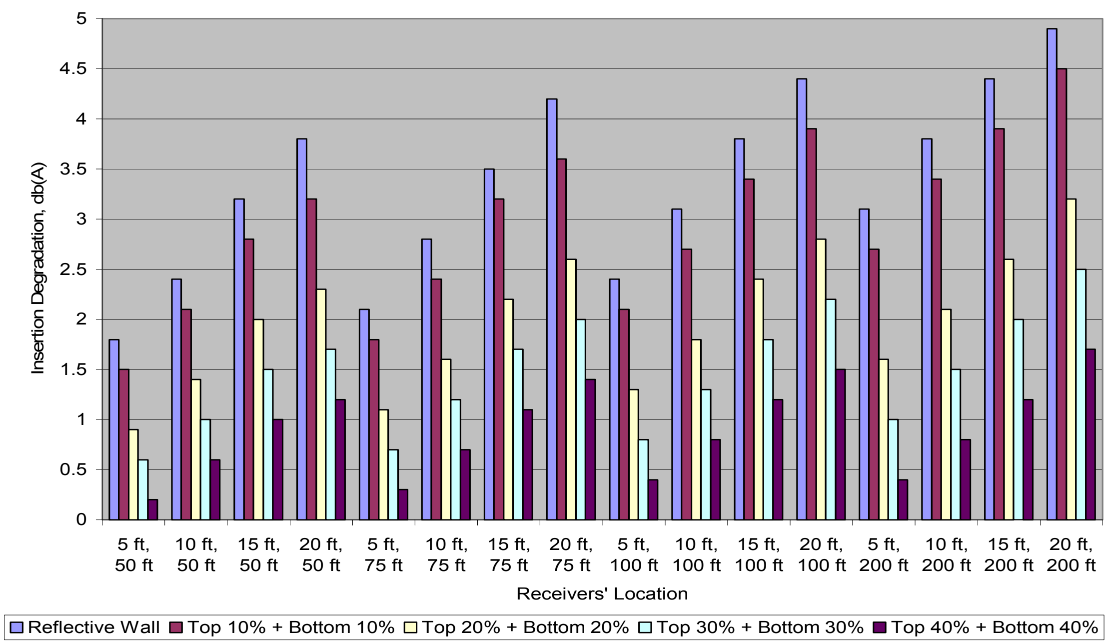


Figure 44: Determination of Best Absorptive Treatment Place with Top and Bottom Spreading Inward Pattern using NRC of 0.85

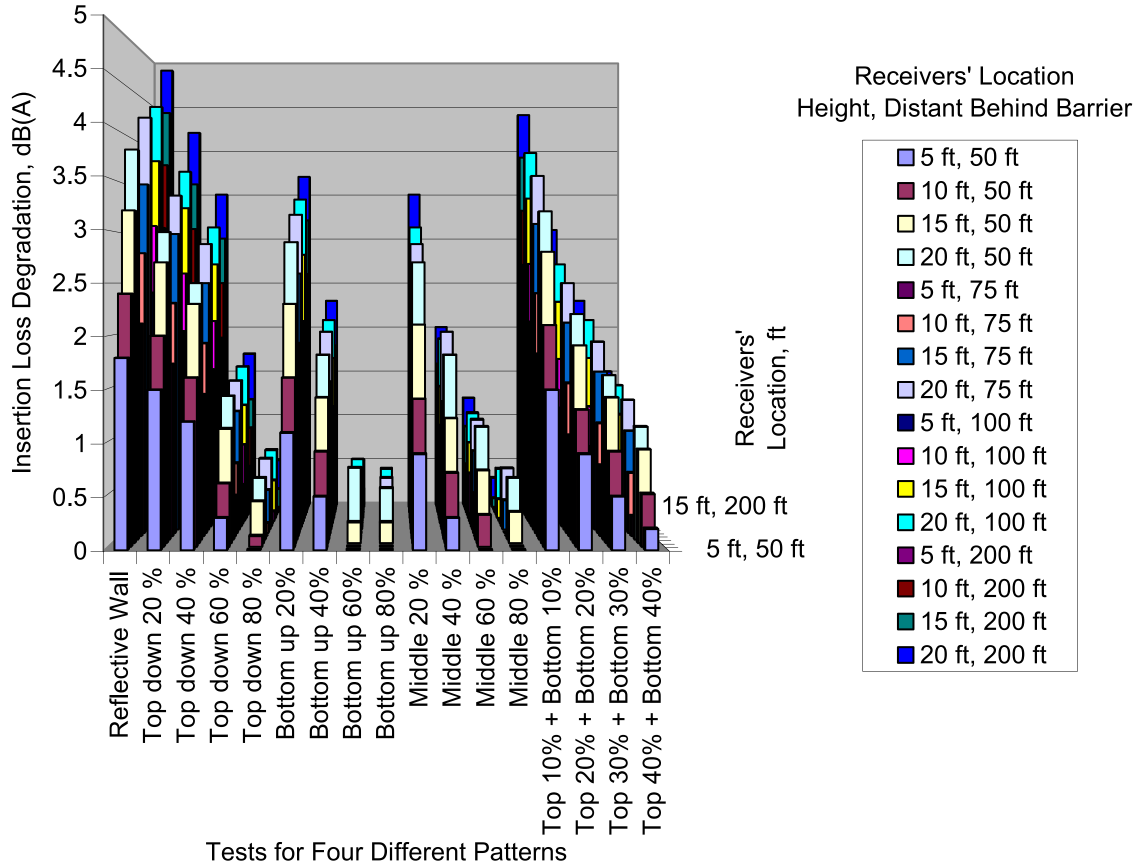


Figure 45: Determination of Best Absorptive Treatment Place with Four Different Patterns using NRC of 0.9

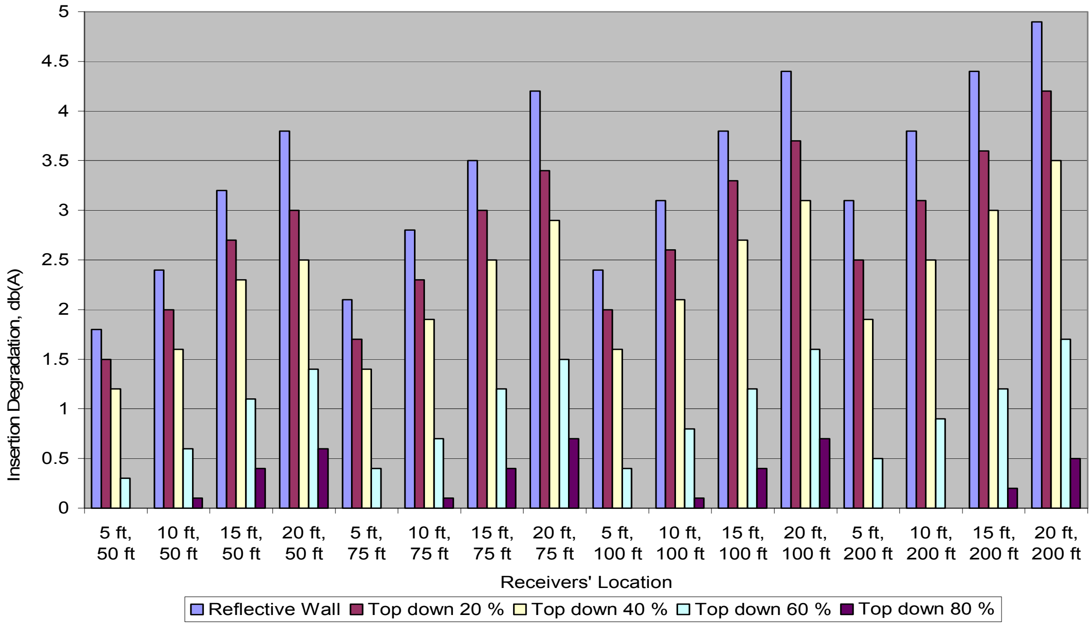


Figure 46: Determination of Best Absorptive Treatment Place with Top Down Pattern using NRC of 0.9

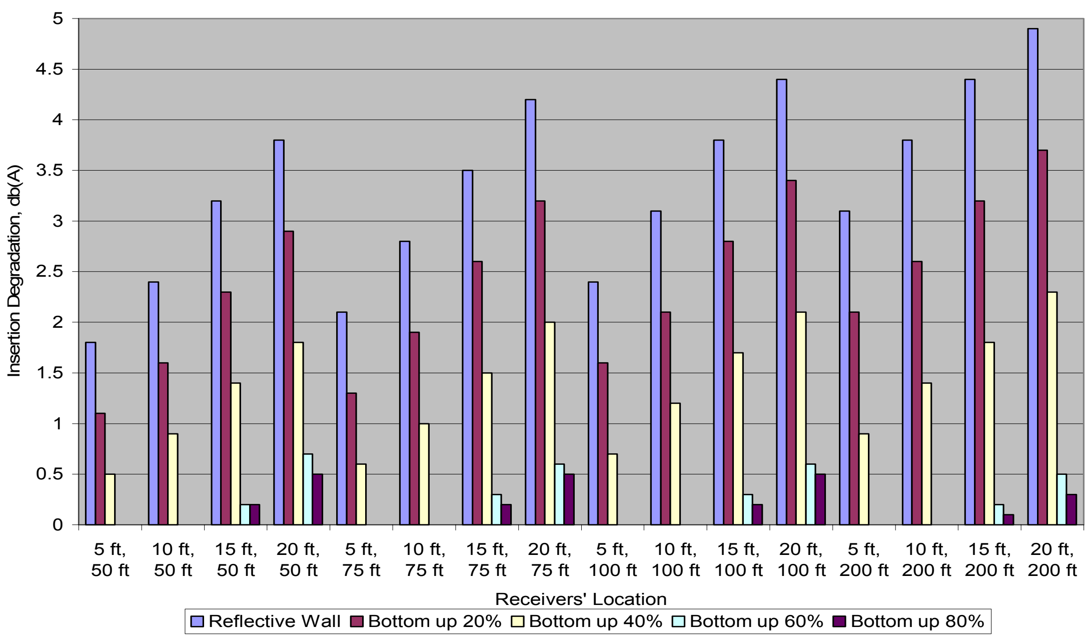


Figure 47: Determination of Best Absorptive Treatment Place with Bottom Up Pattern using NRC of 0.9

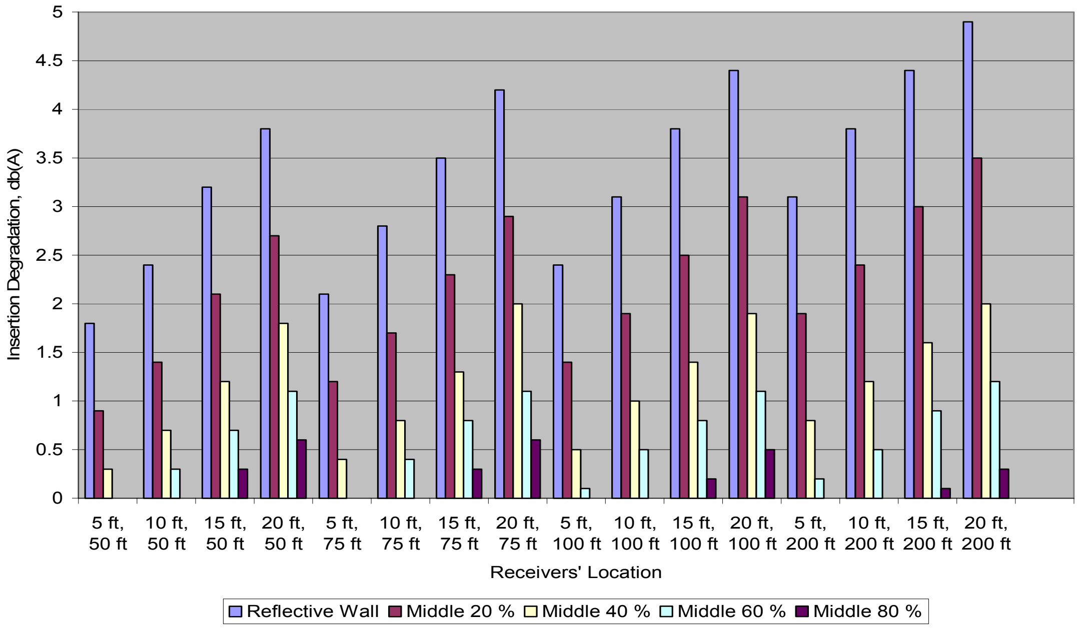


Figure 48: Determination of Best Absorptive Treatment Place with Middle Spreading Outward Pattern using NRC of 0.9

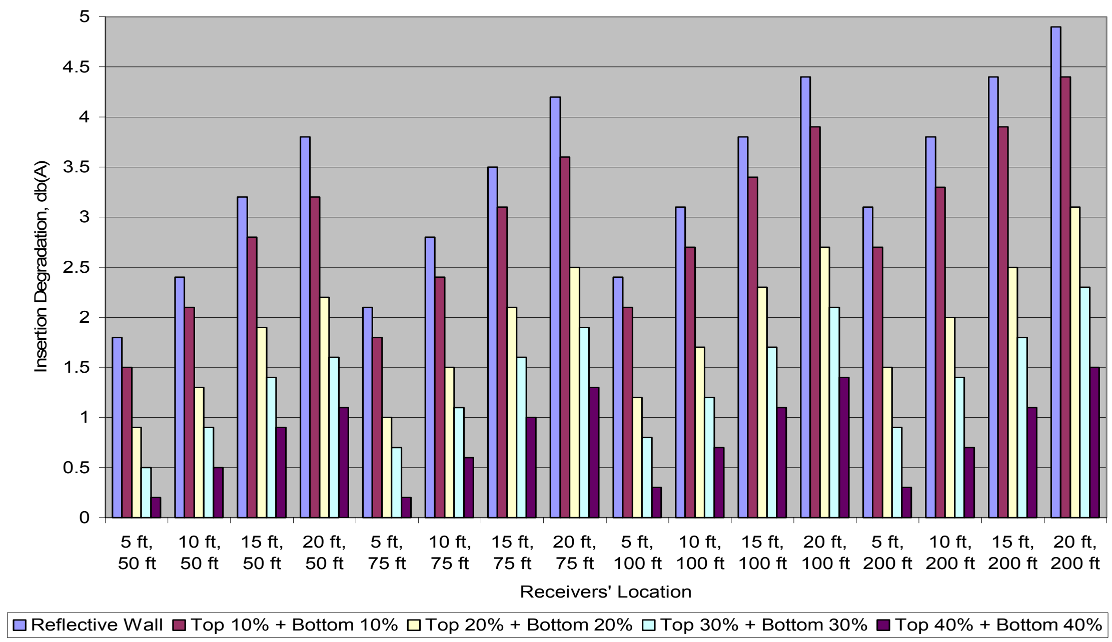


Figure 49: Determination of Best Absorptive Treatment Place with Top and Bottom Spreading Inward Pattern using NRC of 0.9

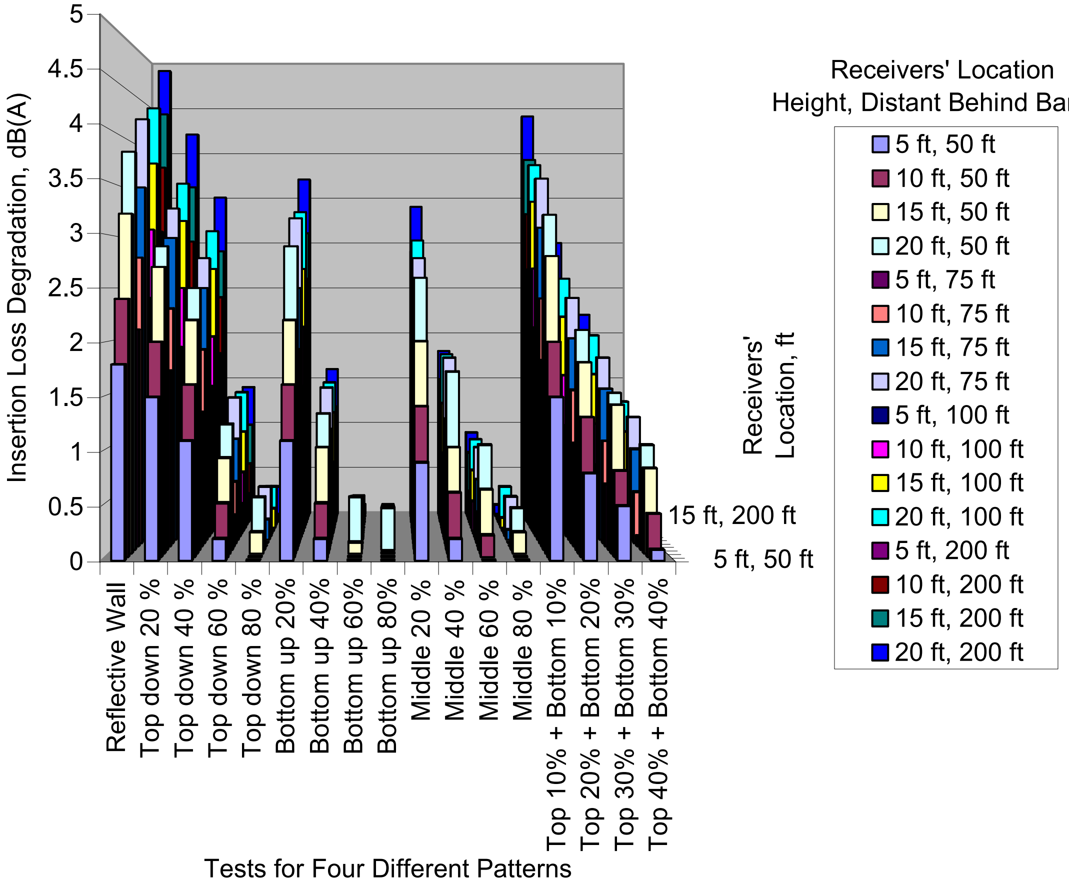


Figure 50: Determination of Best Absorptive Treatment Place with Four Different Patterns using NRC of 0.95

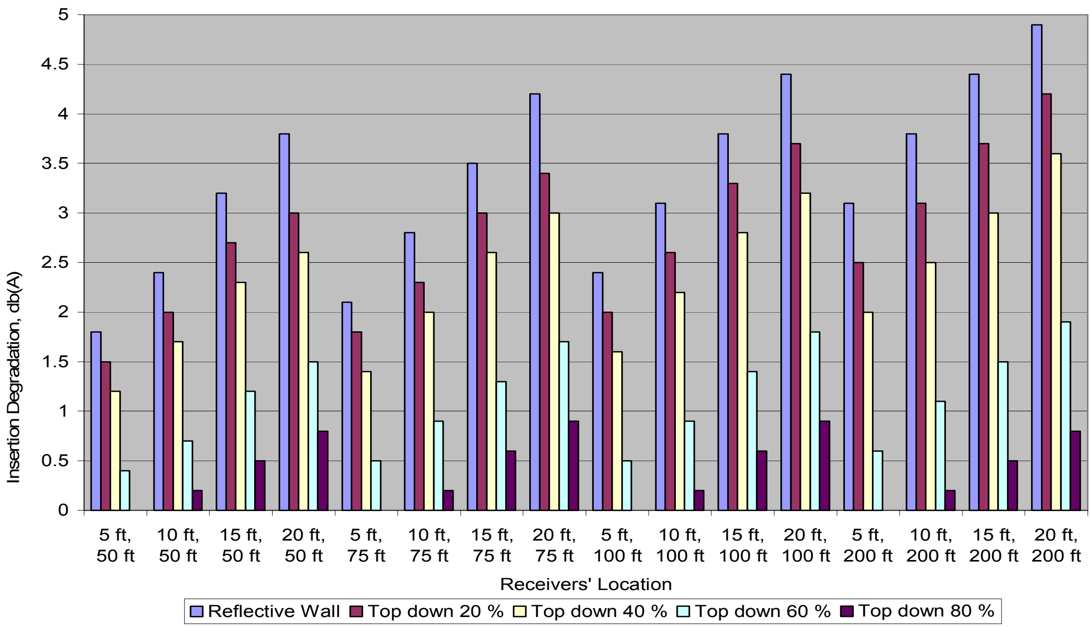


Figure 51: Determination of Best Absorptive Treatment Place with Top Down Pattern using NRC of 0.95

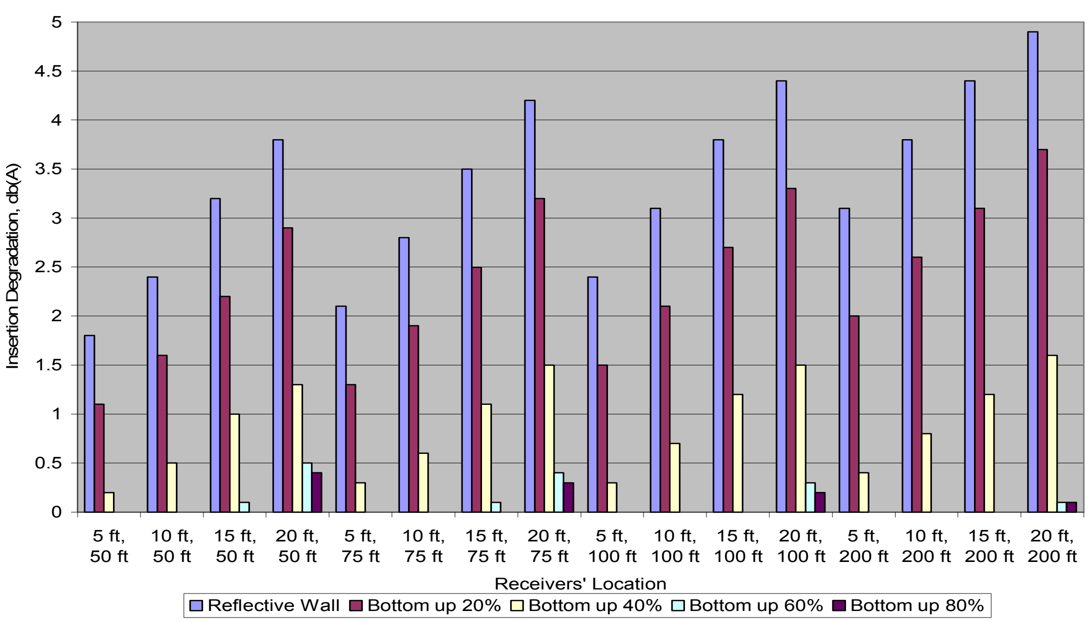


Figure 52: Determination of Best Absorptive Treatment Place with Top Down Pattern using NRC of 0.9

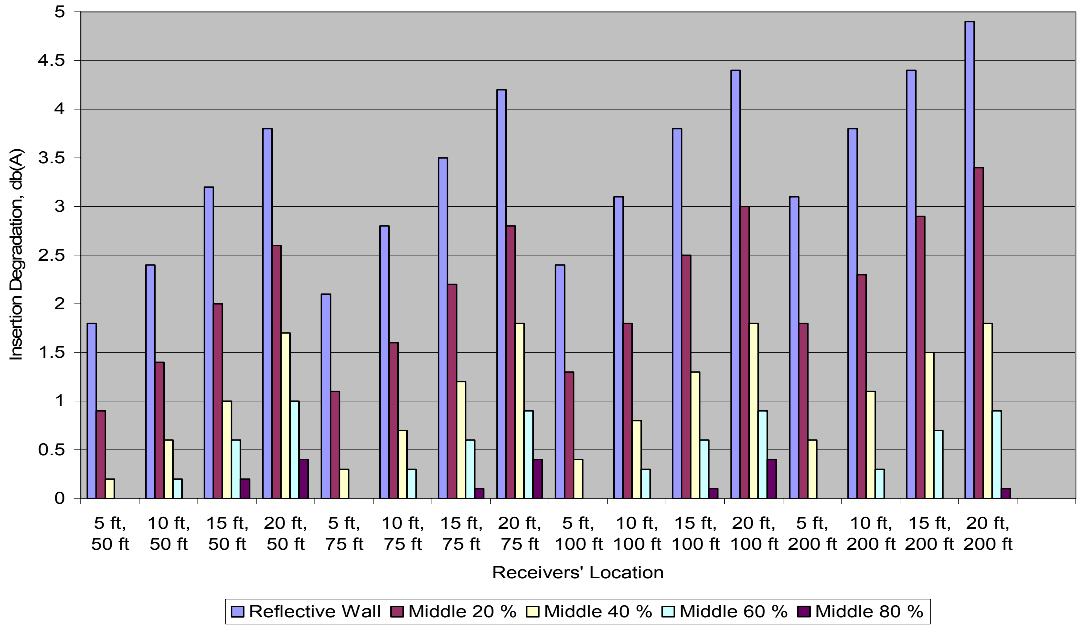


Figure 53: Determination of Best Absorptive Treatment Place with Middle Spreading Outward Pattern using NRC of 0.95

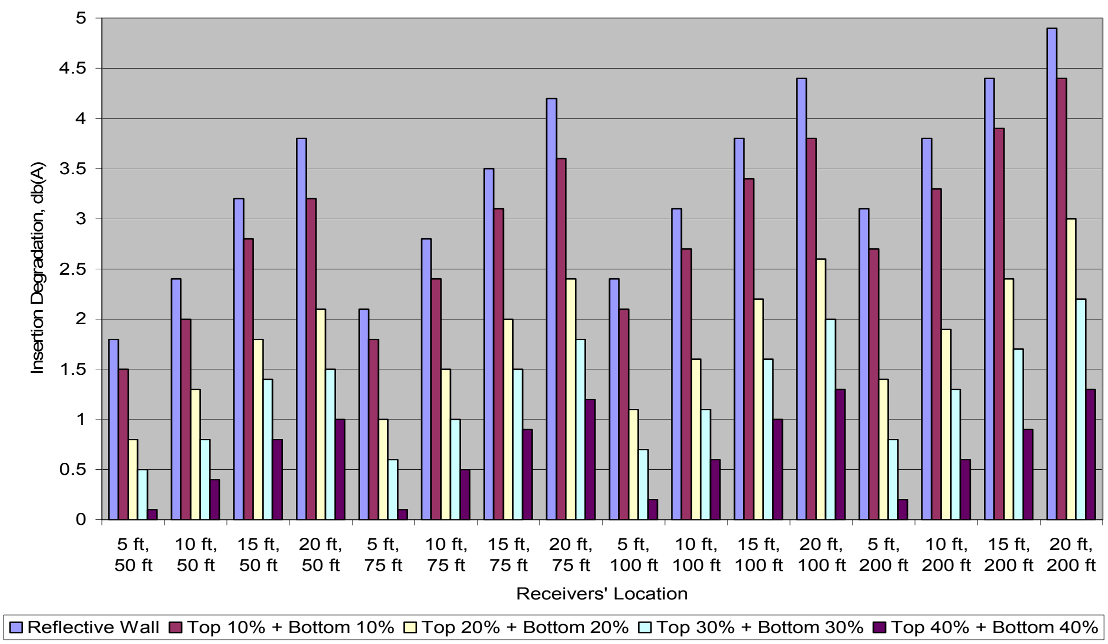


Figure 54: Determination of Best Absorptive Treatment Place with Top and Bottom Spreading Inward Pattern using NRC of 0.9

Absorptive Treatment Material Area Required on Highway Barrier

Figure 55 to Figure 58 are charts created to help visualize required absorptive treatment surface area. This was done by using the best absorptive material placement determined from the previous section, which is the bottom up pattern. It is shown from all four figures that there is a very obvious cut-off point of required surface area that occurs at approximately 60% of the absorptive treatment coverage from the bottom of the barrier with height of 18 feet. Once the coverage exceeds the 60% cut-off point, the improvement of degradation for all the receivers drops to below 1 dB(A) of impact. The additional costs would not seem to be justified. This also confirms why the application of absorptive treatment using the bottom up placement and spreading from the middle patterns were found to be the first and second best placements in the previous section. This finding could substantially reduce the cost of the conventional full coverage absorptive treatment on barriers. Additional work was also done to test for the cut off point for short and tall barriers with height 10 feet and 22 feet, respectively. It was found that cut off point ranges from 55% to 65% for the barrier height from 10 feet to 22 feet tall.

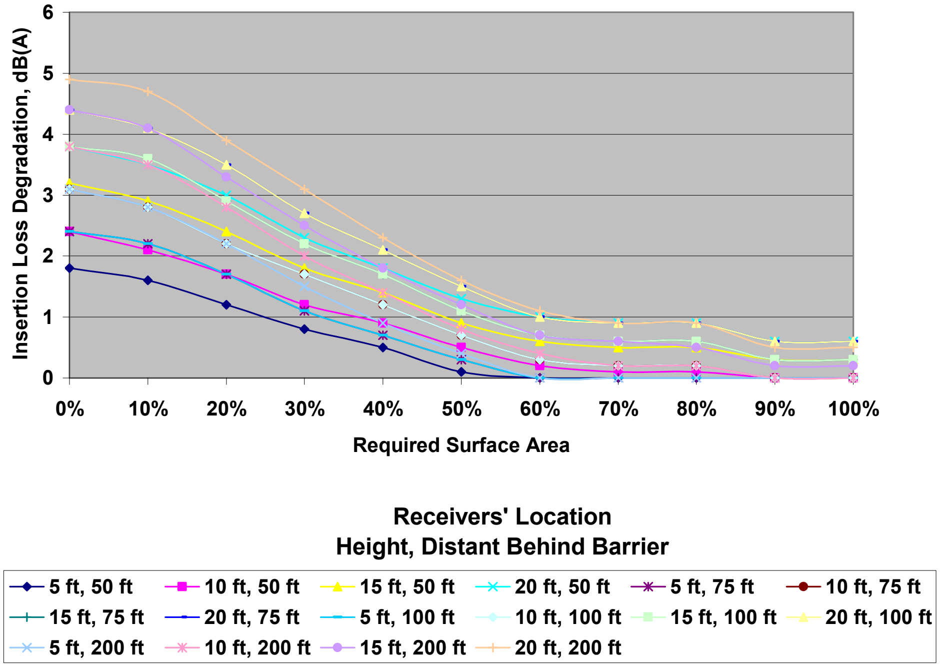


Figure 55: Determination of Cut-off Point on Best Absorptive Treatment Placement Using NRC of 0.8

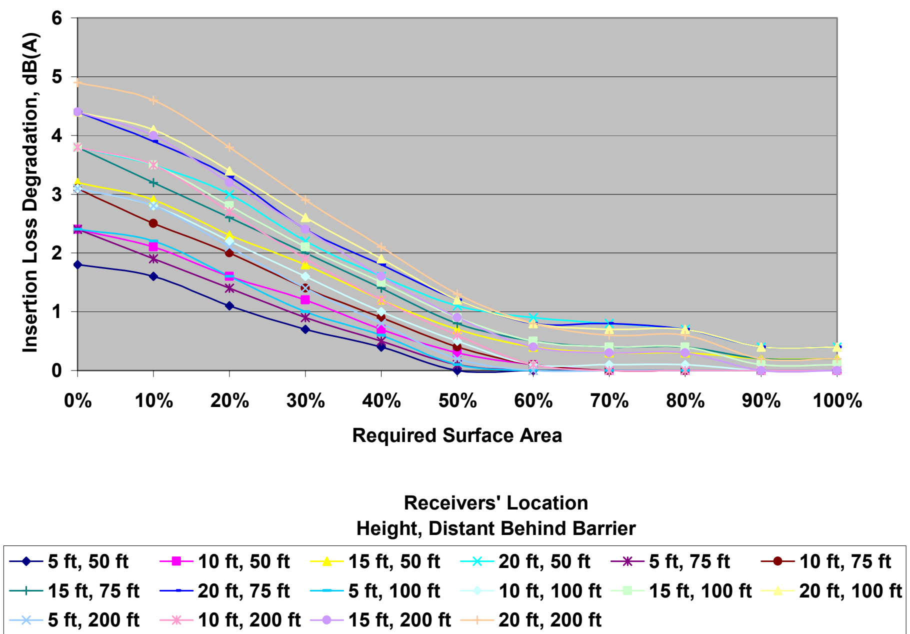


Figure 56: Determination of Cut-off Point on Best Absorptive Treatment Placement Using NRC of 0.85

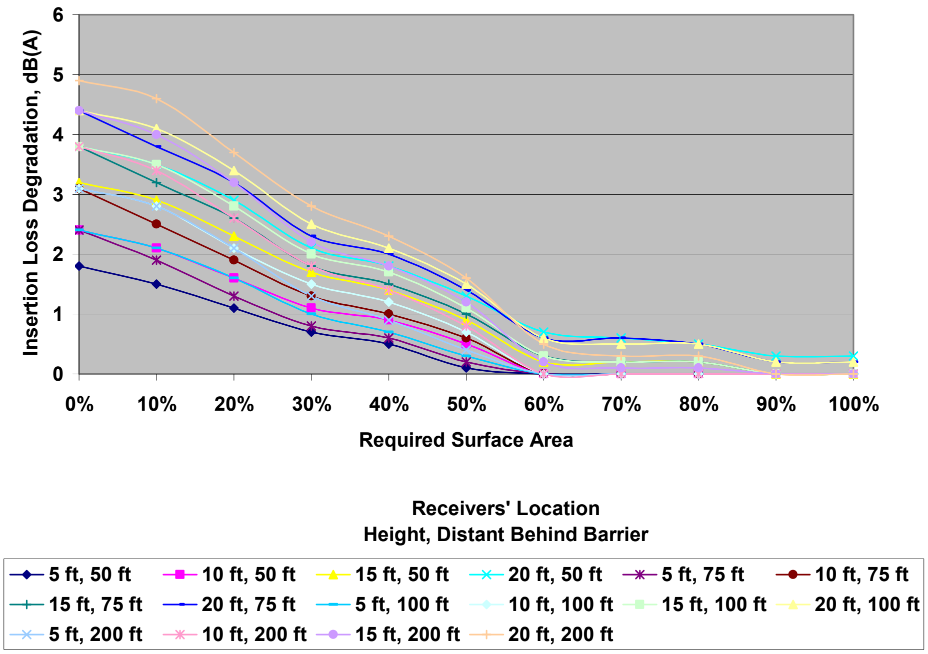


Figure 57: Determination of Cut-off Point on Best Absorptive Treatment Placement Using NRC of 0.9

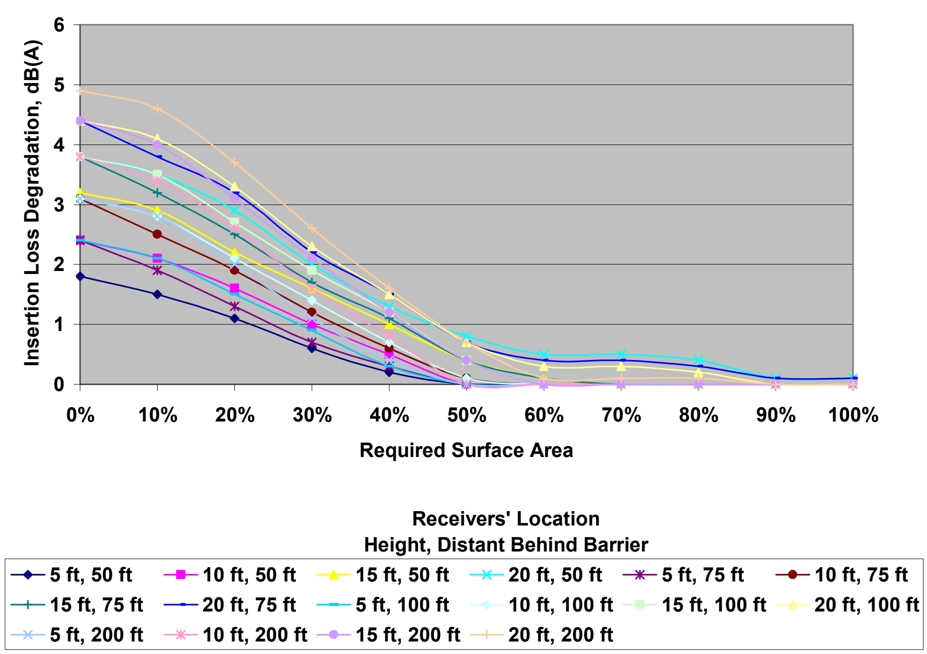


Figure 58: Determination of Cut-off Point on Best Absorptive Treatment Placement Using NRC of 0.95

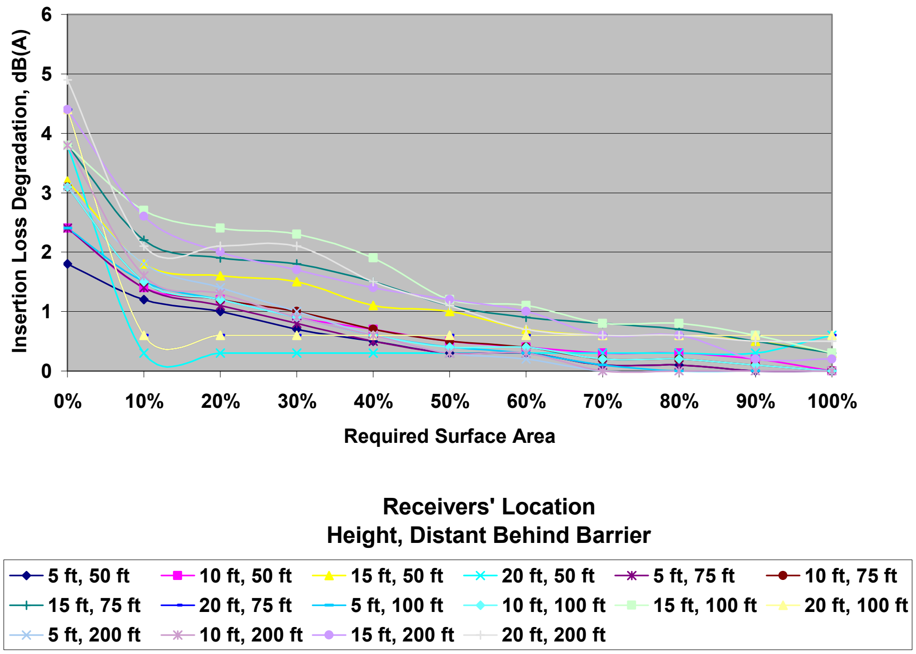


Figure 59: Determination of Cut-off Point on Best Absorptive Treatment Placement for 10-foot Tall Barrier Using NRC of 0.80

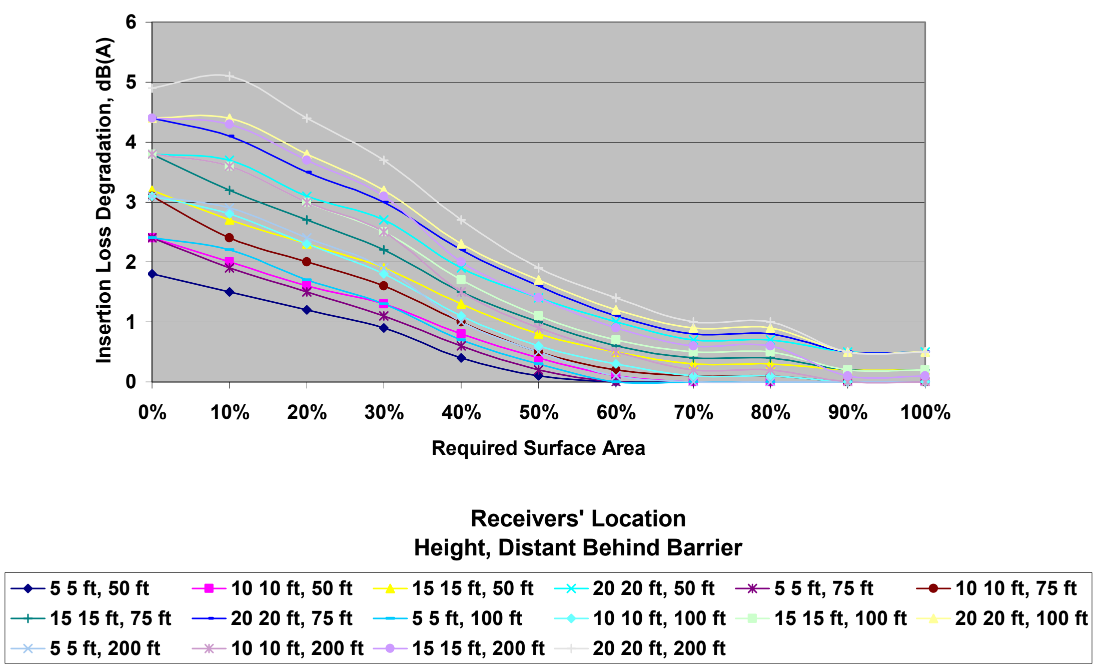


Figure 60: Determination of Cut-off Point on Best Absorptive Treatment Placement for 22-foot Tall Barrier Using NRC of 0.80.

Table 30 and Figure 61 show the results of multiple tests, varying the sections and combining the amount (percent of area) of the absorptive treatment as describe in Figure 29. It was determined that when a low NRC material (NRC = 0.4) was applied to the top section of the barrier, a lesser percentage of high absorptive treatment with NRC of 0.8 or higher could be used on the bottom section without sacrificing insertion loss. In this case, the required area for a high NRC absorptive treatment could be reduced down to only 40% coverage from the bottom. However, the results still show that if a higher NRC value of absorptive treatment is used on the bottom of noise barrier, smaller amount of absorptive treatment area is required.

Table 30: Differences of Insertion Loss Degradation on Modifications if Compared to Base Case

Receivers' Location [Height, Distant Behind Barrier	Base Case	A	B	C	D	E	F	G
		Modifications dB(A)						
5 ft, 50 ft	0	0	0	0	0	0	0	0
10 ft, 50 ft	0.2	0.2	0.3	0.1	0.2	0.2	0.2	0.2
15 ft, 50 ft	0.6	0.6	0.7	0.5	0.6	0.6	0.5	0.6
20 ft, 50 ft	1	0.9	1	0.8	1	0.9	0.8	1
5 ft, 75 ft	0	0	0.1	0	0	0	0	0
10 ft, 75 ft	0.3	0.3	0.4	0.2	0.3	0.3	0.2	0.3
15 ft, 75 ft	0.7	0.7	0.8	0.5	0.6	0.6	0.6	0.7
20 ft, 75 ft	1	1	1.1	0.8	1	0.9	0.9	1
5 ft, 100 ft	0	0	0.1	0	0	0	0	0
10 ft, 100 ft	0.3	0.3	0.5	0.2	0.3	0.3	0.3	0.3
15 ft, 100 ft	0.7	0.7	0.9	0.5	0.7	0.7	0.6	0.7
20 ft, 100 ft	1	1	1.2	0.8	1	1	0.9	1
5 ft, 200 ft	0	0	0.1	0	0	0	0	0
10 ft, 200 ft	0.4	0.4	0.5	0.2	0.3	0.3	0.2	0.3
15 ft, 200 ft	0.7	0.7	0.8	0.5	0.7	0.6	0.6	0.7
20 ft, 200 ft	1.1	1	1.2	0.8	1	1	0.9	1
Average	0.50	0.49	0.61	0.37	0.48	0.46	0.42	0.49

Base Case: – 60% NRC = 0.8, 40% NRC = 0

Modifications:
- A – 50% NRC = 0.8 and 50% NRC = 0.4
- B – 20% NRC = 0.95, 20% NRC = 0.8 and 60% NRC = 0.4
- C – 20% NRC = 0.95, 30% NRC = 0.8 and 50% NRC = 0.4
- D – 10% NRC = 0.95, 40% NRC = 0.8 and 30% NRC = 0.4
- E – 10% NRC = 0.95, 40% NRC = 0.8 and 50% NRC = 0.4
- F – 40% NRC = 0.95 and 60% NRC = 0.4
- G – 40% NRC = 0.95 and 40% NRC = 0.4

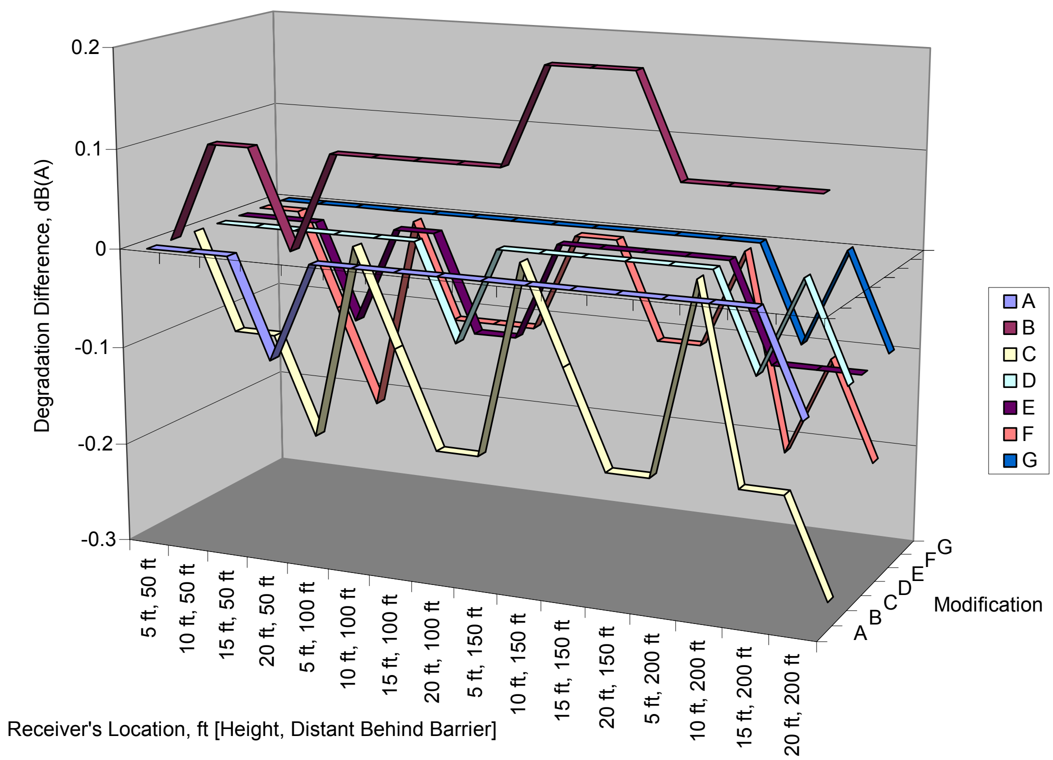


Figure 61: Differences of Insertion Loss Degradation on Modifications if Compared to Base Case

All of the works that described in the previous chapter are shown with their results in this chapter and these include:

1. Selection of three top absorptive treatment materials for Florida highway noise barrier;
2. Results from the developed model;
3. Testing of the derived model against measured/modeled and TNM; and
4. Absorptive treatment material placement and area required.

Conclusions for the results shown in this chapter will be discussed in the next chapter.

CHAPTER FIVE: CONCLUSIONS

The screening criteria for the material selection based on material performances and ranking schemes, namely, the sound absorbing capacity, physical durability, acoustical durability, cleaning and maintenance requirements and flame, fuel, and smoke ratings; the top three absorptive treatments for use on Florida highway barriers have been determined to be cementitous material, metal wool and glass fiber. These materials can be used to reduce the highway impact on the local soundscape caused by sound reflections for single and parallel barriers.

An approximation model using various statistical testing was determined based on a database developed from reporting in the literature. This developed model permits an approximation of the insertion loss degradation that may occur if parallel barriers exist. The developed model from this research is:

$$Deg = -2.17NRC - CW^{0.42} + 1.97\times\ln(BH) + RH^{0.29} + DBB^{0.27} \qquad 10$$

where Deg = insertion loss degradation, dB(A)
NRC = noise reduction coefficient
CW = canyon width, ft
BH = barrier height, ft
RH = receivers' height, ft
DBB = receivers' distant behind barrier, ft

This model can be used as a predetermining tool to determine the magnitude of insertion degradation loss behind parallel barriers instead of using the more approximate FHWA rule of thumb guidance. It does not require complex input data and also is not computer dependent. The input variables for the equation model are simple, and include: noise reduction coefficient, canyon width, barrier height, receiver's height and distant behind the barrier (in feet). This developed model is found to be consistent with the rule-of-thumb guidance postulated by FHWA for determination of insertion loss degradation on parallel barrier and provides a better estimate of the actual degradation amount in dB(A). This model, however, has been generated through a limited range of data from literature, and hence limitations are expected and data input outside of the range of data where it was modeled and generated should be carefully reviewed. This methodology, along with the limited data set, leads to the prediction of negative degradation when the canyon width gets too wide. These negative readings should be considered to be insignificant degradation and might not even be measurable.

The model was tested against insertion loss values that were derived from a comparison of measured and predicted values (measured/modeled values) using ANSI method. It was assumed that the Federal Highway Administration model TNM predicts diffraction well because it's one of its primary functions is the design of noise barriers. Variances were shown between measured and predicted values. These results were found to be consistent with the results from the developed model, providing further proof of the validity of the model.

The model was also tested against insertion loss values that were derived from the TNM Parallel Barrier Module. It was found that TNM tended to predict larger insertion loss degradation for all receivers if compared measured/modeled results and the results from the developed model.

The most effective placement of absorptive material was found to be the pattern which covers the barrier from the bottom up. It was also found that the cut-off point based on cost effectiveness would seem to be when approximately 60% of the area from the bottom of the barrier is covered with an absorptive treatment with an NRC of at least 0.8. These 2 findings are probably due to the absorption of sound waves produced by the tire/pavement noise and the angles that are created causing a reverberant parallel barrier canyon situation.

It was also found that combining and varying the NRC can further reduce the required absorptive treatment area. Combining a relatively low NRC of 0.4 that is easily obtainable on the top portion of the barrier, the needed, higher NRC absorptive material could be limited to the bottom 40% of the barrier. These findings can substantially reduce the cost of conventional absorptive barrier which have full coverage of high NRC absorptive treatment. It is also assumed that the best placement and required area can be used to improve the degradation in single barrier cases which can cause annoyance to residents on the opposite site of the highway.

In conclusion, for typical Florida barrier configuration, the generated equation model can be used as a predetermining tool to determine the magnitude of parallel barrier insertion loss. If the degradation requires treatment, one of the 3 absorptive treatment materials (cementitous materials, metal wool and glass fiber) would seem to be the best choice for use in Florida. Only about 60% from the bottom of the barrier area requires high NRC absorptive treatment. If the barrier area near the top includes an easily obtainable NRC value of 0.4, only 40% to 50% of the bottom barrier needs absorptive treatment with a higher, more expensive NRC rating.

CHAPTER FIVE: RECOMMENDATIONS

In the future, it is recommended that noise barrier constructors in Florida consider the following steps to design a cost effective absorptive highway noise barriers when needed to minimize the insertion loss degradation:

1. According to the design goal, determine the single barrier height;
2. Use Equation 9 to determine insertion loss degradation.
3. Select one of the 3 top absorptive treatment material with cost being an important consideration;
4. Use the best absorptive treatment placement and 60% required area to determine the degradation improvement.
5. If necessary, go back to step one to increase the height. The increase of barrier height should be very small and is unlikely to increase degradation much.
6. Base on the step 3, try to vary the absorptive treatment with different NRC by using economy low NRC material on the top and high NRC material on the bottom;
7. Determine the best combination in terms of cost factor for the final analysis.

Future Research

This research has begun important improvements in noise barrier design. But the literature is somewhat limited and more work is needed. This additional work includes:

1. Field measurements to collect data for parallel barrier to further improve the equation model and also TNM parallel barrier algorithms.
2. Creation of design charts for absorptive treatment placement and area requirement.
3. Determination of the most cost effective absorptive barrier by exploring even more combination of absorptive material used.
4. Verify the use of best absorptive treatment placement found and area required by conducting full scale measurement. If this is proved to be the case, it can save the industries substantial amount of money.

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